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FOREWORD

The research described in this report, *Experiments Concerning the Hartmann Whistle,* by T. J. B. Smith and Alan Powell, was carried out under the technical direction of Alan Powell and is part of the continuing program in Fluid Motion and Sound.

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ABSTRACT

The Hartmann whistle, in its most basic configuration, consists of a flat-bottomed, cylindrical cavity which is axially aligned with a supersonic air jet of the same diameter. Discrete-frequency oscillations of the enclosed air column are driven at large amplitudes when the cavity is located within certain regions of the cellular structure of the jet. An optical and acoustical study of the phenomenon is described, together with that of the Hartmann 'pulsator'. In the latter form the whistle has the small cavity replaced by a large Helmholtz-type resonator with the same orifice diameter, resulting in a large-amplitude aeroacoustic oscillator with a periodic time of several orders of magnitude greater than for the regular whistle. The underlying cause of the newly discovered bistable condition of the normal 'shock-disc' located in the airstream between the nozzle and the cavity orifice is an important aspect which makes possible a (presently qualitative) theory of operation which accounts for the principal features of the Hartmann whistle and its direct derivatives. Some other aspects still requiring further elucidation and which are the subject of continuing effort are mentioned. The Report includes a brief review of the currently available literature pertaining to the phenomenon.

A SCHLIEREN STUDY OF THE HARTMANN WHISTLE †

INTRODUCTION

In certain divisions of engineering technology there is a growing need for high-powered, discrete-frequency acoustic generators having outputs which range from low audio-frequencies to extreme ultrasonic. The applications of such generators are many and varied and in general make use of the ability of high-intensity acoustic radiation to control combustion processes, coagulate dusts and aerosols, emulsify liquid mixtures, cause fatigue failures of certain structures and the like. To date most of the work of this nature has been limited to small-scale experimentation, but proven applications of airborne acoustic radiation to production engineering techniques are becoming more and more widespread. The aerospace industries, for instance, make use of high-powered sonic generators for studies of fatigue failures of airframes and space vehicles[1], for short-range signalling, and for combustion control in solid propellant rocket motors[2]. There are many potential applications of sonic energy to chemical engineering processes, such as the precipitation and agglomeration of foams and aerosols, gas cleaning, powder drying and the acceleration of certain chemical reactions[3]. In other branches of manufacturing and production, sonic radiation has been shown to aid cleaning and de-greasing operations and to increase the combustion intensities of oil- and gas-fired burners[4]. It is obviously desirable that the efficiencies of such generators shall be as high as possible if the envisaged industrial processes are to be economically viable, and for this reason, together with many other significant advantages, high-powered whistles are being developed for an increasing number of applications[5,6].

†Certain aspects were previously reported by Alan Powell and T.J.B. Smith at the Sixty-Fourth Meeting of the Acoustical Society of America (see J. Acoust. Soc. Am. 34, 1984 (A), 1963) and by T.J.B. Smith and Alan Powell at the Sixty-Seventh Meeting (J. Acoust. Soc. Am. 36, 1018 (A), 1964).

The types of acoustic generator used for the purposes listed above may be divided into three main categories: aerosonic, aero-mechanical and electro-mechanical. The two latter forms utilize the flexure or periodic displacement of a component part, either to interrupt a fluid flow (as in the case of a rotating siren) or to generate pressure-wave radiation directly (as in the case of most magnetostrictive, piezoelectric or electromagnetic transducers.) On the other hand, aerosonic generators contain no oscillating parts and depend on a combination of a fluid flow and a fixed component of predetermined geometrical configuration to give rise to acoustic radiation, as in the case of a simple whistle or organ pipe. Aerosonic devices may be conveniently classified as 'static' devices, in contrast to aero- and electro-mechanical transducers which embody moving components, and hence will be referred to as 'dynamic' generators.

Static generators have many advantages over all other types--they are simple to construct, require little maintenance or alignment and are of inherently rugged construction since they may be made entirely from corrosion- and temperature-resistant materials. They require only a supply of compressed air or steam in the way of ancillary equipment, and, having no electrical connections, may be used in explosive atmospheres--an important consideration where sonic energy is to be applied to combustion control or certain chemical processes.

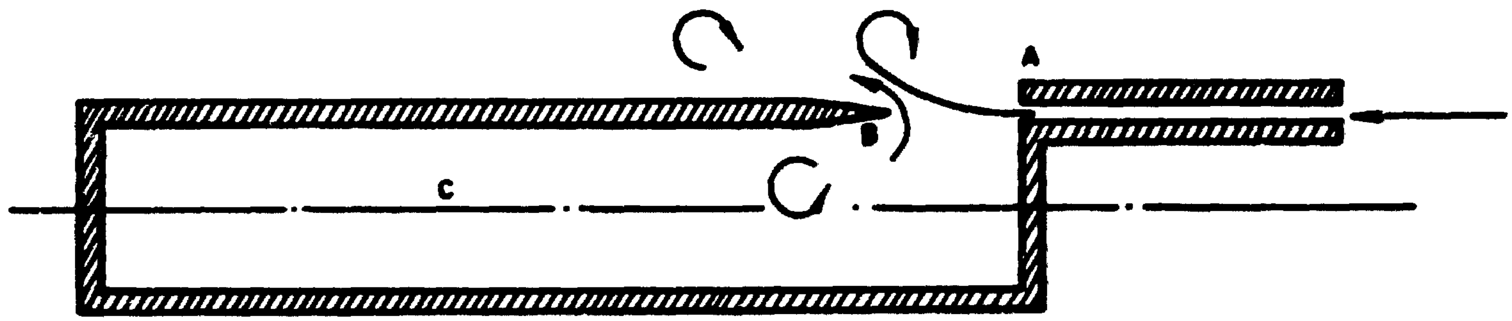
Four main forms of static generator are recognized. These are the Galton whistle, the Levavasseur whistle, the vortex whistle and the Hartmann whistle. The first two are derivatives of the simple organ pipe and depend for their operation on mechanisms related to subsonic and supersonic edge-tone phenomena. The mechanisms of the vortex and Hartmann whistles are, as yet, not fully identified and the latter will form the basis of this report. (The reader is referred to the work of Chanaud[7] for the most complete account to date of sound generation by vortex whistles.)

The phenomenon which now bears his name was discovered by J. Hartmann of Copenhagen in 1916 during the course of experimental investigations of the axial stagnation pressure distribution along supersonic jet effluxes. He found that there were certain points in the jet stream where high-amplitude oscillations of the pressure-probe assembly were driven, a discovery that initiated his investigations of the oscillations of other forms of closed cavities placed in the supersonic flow. Since then the phenomena has been studied by many researches (notably by Hartmann and his co-workers) but none have yet been able to account for all aspects of the phenomena in a suitable theory for the initiation and maintenance of the oscillations.

Static Aerosonic Generators

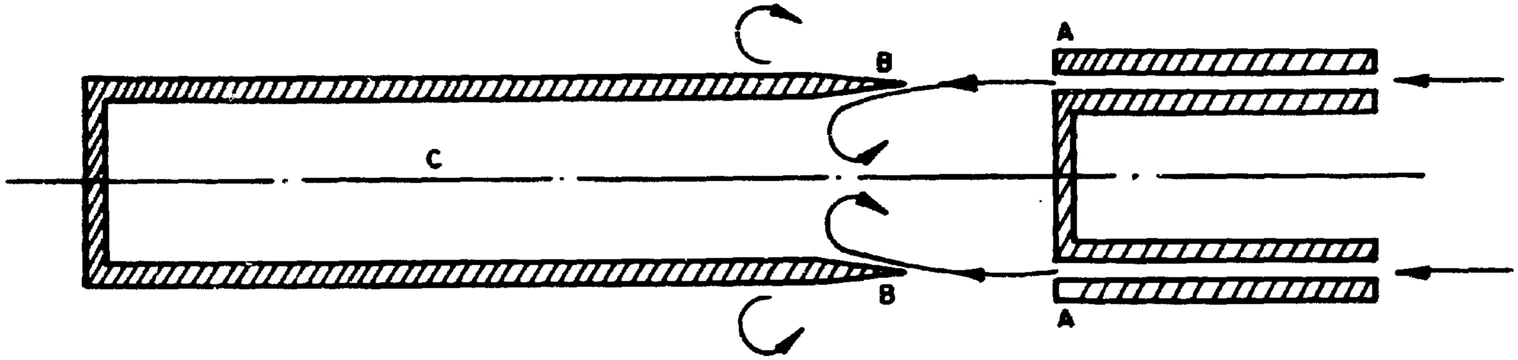
The tuned cavity excited by a low-velocity air jet has formed the basis of many musical instruments since prehistoric times, and in its simplest form is represented by the whistle shown in Fig. 1a. A planar jet issuing from a slit orifice A is arranged to impinge on an edge B, giving rise to an edge tone for a specific range of flows and-jet-to-edge distances. The tuned cavity C gives rise to "forced" edge-tones[8]. The acoustic output of such a device is low, but it may be slightly increased in the case of the Galton whistle[9]. This is essentially a rotationally symmetrical device, consisting of the upper section of Fig. 1a rotated about its longitudinal axis. Hence one obtains a quarter-wave resonant cavity excited by a coaxial annular edge-tone, again with a relatively low acoustic efficiency, but capable of high frequencies and very pure outputs (Fig. 1b.)

Very much greater acoustic powers are obtainable from these two whistles when the excitation jets exceed the critical pressure, since the supersonic edge-tones excite violent oscillations of the enclosed air columns. Such oscillations are no longer classifiable as 'small perturbations' and due to their non-linearity the emitted sound contains a high proportion of both odd- and even-numbered harmonic components. Because of the absence of data pertaining to the supersonic edge-tone phenomena, the mechanism of the high-pressure Galton whistle is only partially understood, but research is proceeding on the elucidation of its action. A commercially successful high-pressure version of the simple whistle illustrated in Fig. 1a, known as the



ORGAN PIPE

FIGURE 1a



GALTON WHISTLE

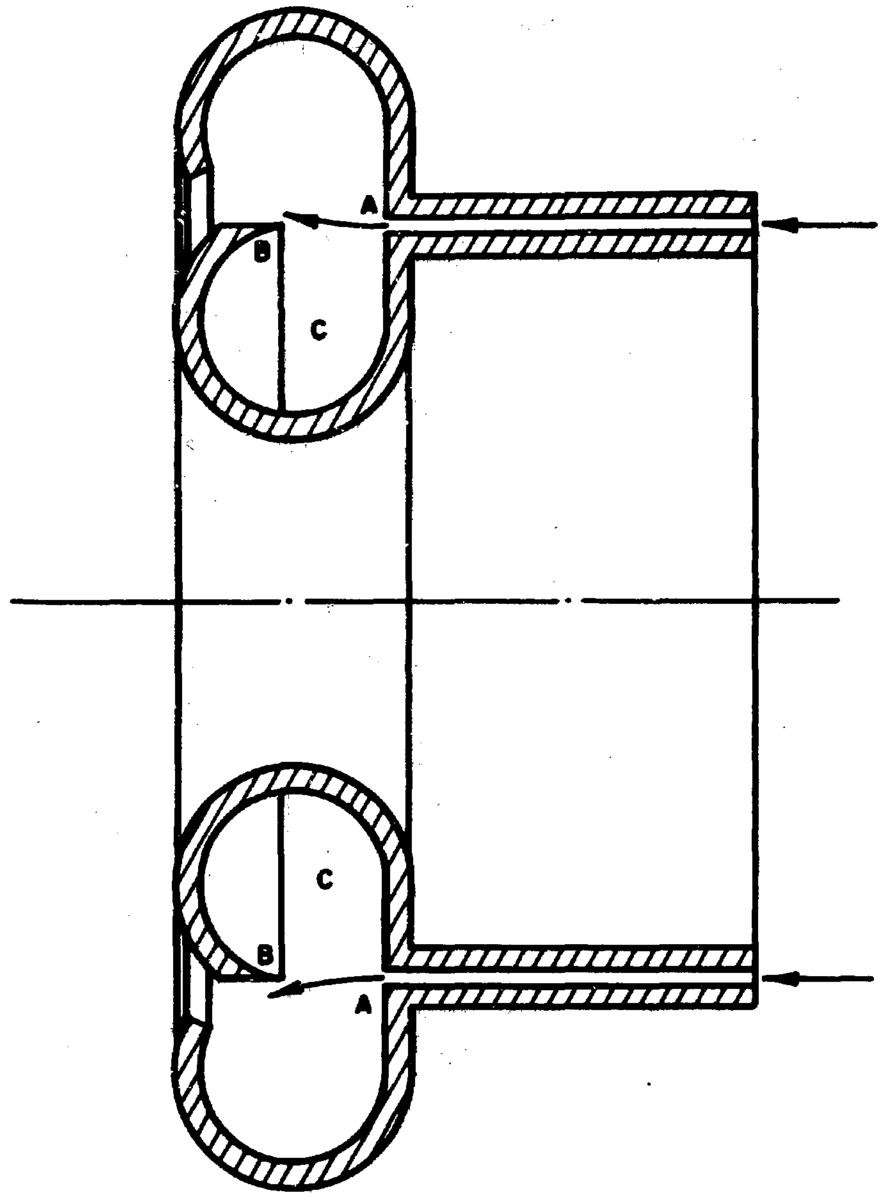
FIGURE 1b

Levavasseur whistle, has been developed for which efficiencies ranging from 5% to 15% are claimed, but again with only a partial understanding of its operation[10]. (The Levavasseur whistle is the alternate rotationally symmetrical derivative of Fig. 1a, consisting of the cross-section rotated about an external datum. The example shown in Fig. 1c contains two toroidal cavities--a refinement that has been found by experiment to augment its output.)

The Hartmann whistle differs from the foregoing examples in that it has been shown to be largely independent of the classical edge-tone phenomena for its operation. It consists, in its most basic form, of a cavity whose open end is axially aligned with a high speed gas jet, or in some cases with an external supersonic air stream. When the jet velocity exceeds sonic speed violent oscillations of the contained gases in the cavity are driven at or near one of its resonant harmonic frequencies. Consequently intense discrete-frequency acoustic radiation (in some cases over 150 watts[11]) is emitted from the open end at a relatively high aeroacoustic efficiency.

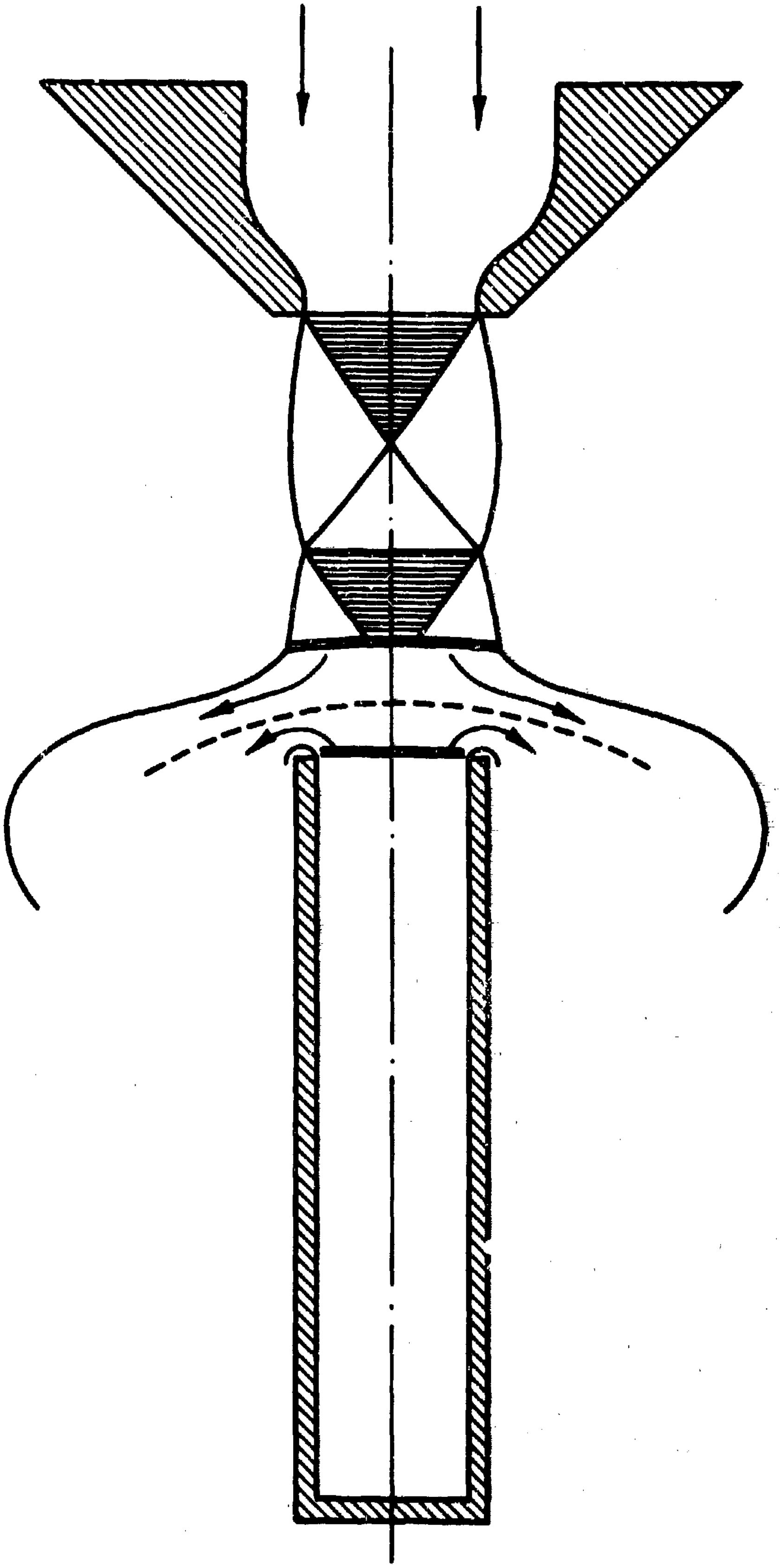
It has been found that weak oscillations of the air column can be excited by a subsonic jet, but in such a case the combination of geometric and flow parameters describing the necessary configuration for resonance is very critical, implying perhaps that the mechanism of this type of oscillation is due to some form of vortex generation, after the manner of the edgetone. In the normal (supersonic) case these parameters are much less significant, oscillations being driven over a wide range of pressures, jet-to-cavity distances and cavity dimensions. More information will be provided on this aspect of the phenomenon in ensuing sections.

The cavity is usually in the form of a closed, cylindrical, flat-bottomed resonator whose ratio of length to diameter may range from 0.25 to 50 or more, the jet nozzle and cavity usually being of similar diameters (Fig. 2a). Very low-frequency oscillations (of the order of 0.5 c/s. or less) may be obtained by using a large Helmholtz resonator as the cavity, sometimes referred to as the 'Hartmann pulsator'. Resonant cavities located in supersonic airstreams with their orifices directed towards the flow often emit discrete-frequency sound of high intensity, especially if a 'de-stabilizing



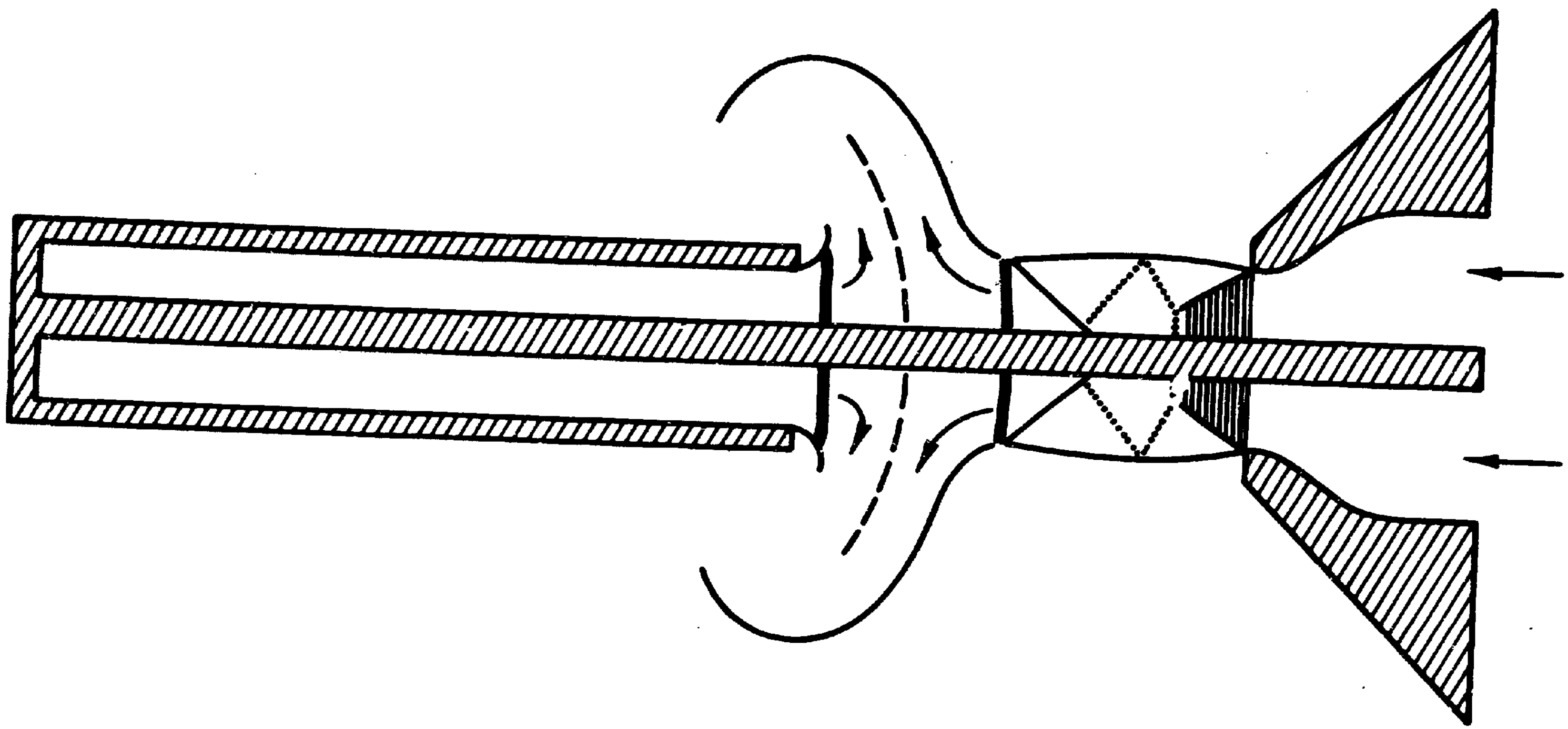
LEVAVASSEUR WHISTLE

FIGURE 1c



HARTMANN WHISTLE

FIGURE 2a



HARTMANN 'STEM-JET' WHISTLE

FIGURE 2b

trip' is located upstream of the cavity, or if the orifice is oblique. These oscillations are thought to have much in common with those of the Hartmann whistle[12]. It is of interest to note that the phenomenon appears to be associated with ram-jet instability (ram-jet 'buzz'), particularly where a diffuser spike located forward of the inlet orifice acts as a de-stabilizer[13-17]. From this it may be inferred that if any resonant cavity is included in a supersonic airframe there is a possibility that, when the orifice of such a cavity is directed toward the direction of flight, undesirable oscillations may occur, together with an associated heating effect at its base (an aspect of the phenomenon that will be described in ensuing sections). It has also been hypothesized that the deep pits found in certain meteorites arise as a result of cavity resonance during the passage of the body through the atmosphere, the large-amplitude oscillations aiding the ejection of molten material from the pits[18].

The heating effect referred to in the foregoing paragraph is a further ramification of the overall problem which has been the subject of much research. It was mainly overlooked by early researchers who used short, thick-walled resonant tubes surrounded by large heat sinks (the massive supports and clamps). Hartmann detected a temperature rise of only 7°C at the base of an oscillator having a length and diameter of 8 mm but later investigators using long, thin-walled tubes showed that the bases of such cavities were heated to temperatures much greater than the stagnation temperature of the jet when oscillations of the enclosed gas were driven. Sprenger reported that cavities cut in wood or paraffin wax would become greatly enlarged by the heat generated and that tubes made of German silver distorted and melted[19].

Researchers whose main interest was this particular phenomenon have used the term 'resonance tube' to describe the apparatus used. Other names given to it have included: 'gas jet siren', 'static siren', 'air-jet generator', 'jet-type vibrator', etc., but the authors have adopted the term used by Boucher (the 'Hartmann whistle') as being the least ambiguous, albeit not the most self-descriptive terminology.

Previous Research

The first announcement of his discovery was made by Hartmann in 1919 as a result of a series of experiments that he had been conducting to determine the nature of the stagnation pressure distribution along the axis of a spatially-periodic supersonic jet[20]. He found that violent oscillations occurred in the pitot tube whenever its orifice was located near points in the jet efflux where the stagnation pressure increased with distance from the jet nozzle. He identified the oscillations as being acoustic, the wavelength of the sound emitted being some function of the longitudinal dimensions of the pitot tube assembly. This led him to try further experiments using a large Helmholtz resonator in place of the pitot tube, a configuration which he referred to as a 'pulsator'. The system was found to oscillate with an extremely low frequency (of the order of a few cycles per minute) which facilitated optical observation of the external flow during the resonant cycle by means of a schlieren and shadograph system. It was noted that the cycle showed two major flow conditions. For approximately half the periodic time jet efflux appeared to flow directly into the cavity, with the external detached shock disc (the Reimann wave) situated close to, or within the pulsator orifice. Suddenly, the flow would reverse--there would be an impulsive movement of the normal shock in an upstream direction and the cavity would debouch. As the pressure in the cavity dropped, the location of the transverse shock moved downstream until another sudden reversal of flow occurred and the jet would re-enter the cavity until the next debouchment, and so on.

Hartmann made further experiments with very small cylindrical cavities, some having a depth and diameter of only 0.5 mm. Spark-schlieren photographs showed that the external flow variations occurring during resonance of one of these cavities were essentially the same as occurred with the pulsator. It was noted that the oscillations were driven when the cavity mouth was located near the maxima in the total-pressure distribution curve for the air jet--no oscillations being driven near the minima. This observation gave rise to Hartmann's theory for the mechanism of the phenomena, which relates these 'intervals of instability' to his surveys of the stagnation pressure variation along periodic jets. His modus operandi may be summarized with

reference to Fig. 3 (based on a diagram appearing in Reference 25) in the following manner:

(1) The cavity N_2 first fills to the equilibrium pressure C existing in the jet stream at the location of the cavity orifice.

(2) Some small flow disturbance allows the air to commence escaping from the cavity, giving rise to a supersonic jet from its orifice.

(3) The periodic axial pressure distribution of the cavity flow P_2 exceeds that of the main jet P_1 over a finite distance ac upstream of the cavity. The secondary jet impinges on the main jet and the cavity debouches until the primary jet again overcomes the debouching air mass C" and refills the cavity for the next cycle.

(4) The frequency of the cyclic phenomenon is governed by the natural frequency of the cavity due to some unspecified wave motion within it.

This hypothesis has been shown to be partially correct in that it accounts for the observed cyclic variations of the flow and indicates the connection between the spatial pressure periodicity of the jets and the 'intervals of instability'. However it does not indicate how the small 'flow disturbance' initiates each successive cycle, or how wave motion in the cavities controls the frequency of the cyclic flow phenomena. (There cannot be any similar travelling wave effects within the pulsator cavity, where the wavelength is several orders of magnitude greater than its longest dimension). Neither does the postulated mechanism take into account the presence of the detached shock in front of the cavity, or of its potential instability or the conditions in the stagnation region behind it.

Over a period of thirty years Hartmann and his several co-workers regularly published their interesting investigations on the phenomenon[21-34]. The later part of their work was mainly directed towards the development of an efficient acoustic tool for laboratory and industrial use, the experimental procedure consisting mainly of ad hoc modifications of the original configuration with the object of developing maximum efficiency and an extension of the working range of pressures and characteristic dimensions. However, no attempt was made to modify the many shortcomings of the proposed modus operandi in the light of later findings, some of which were at variance with

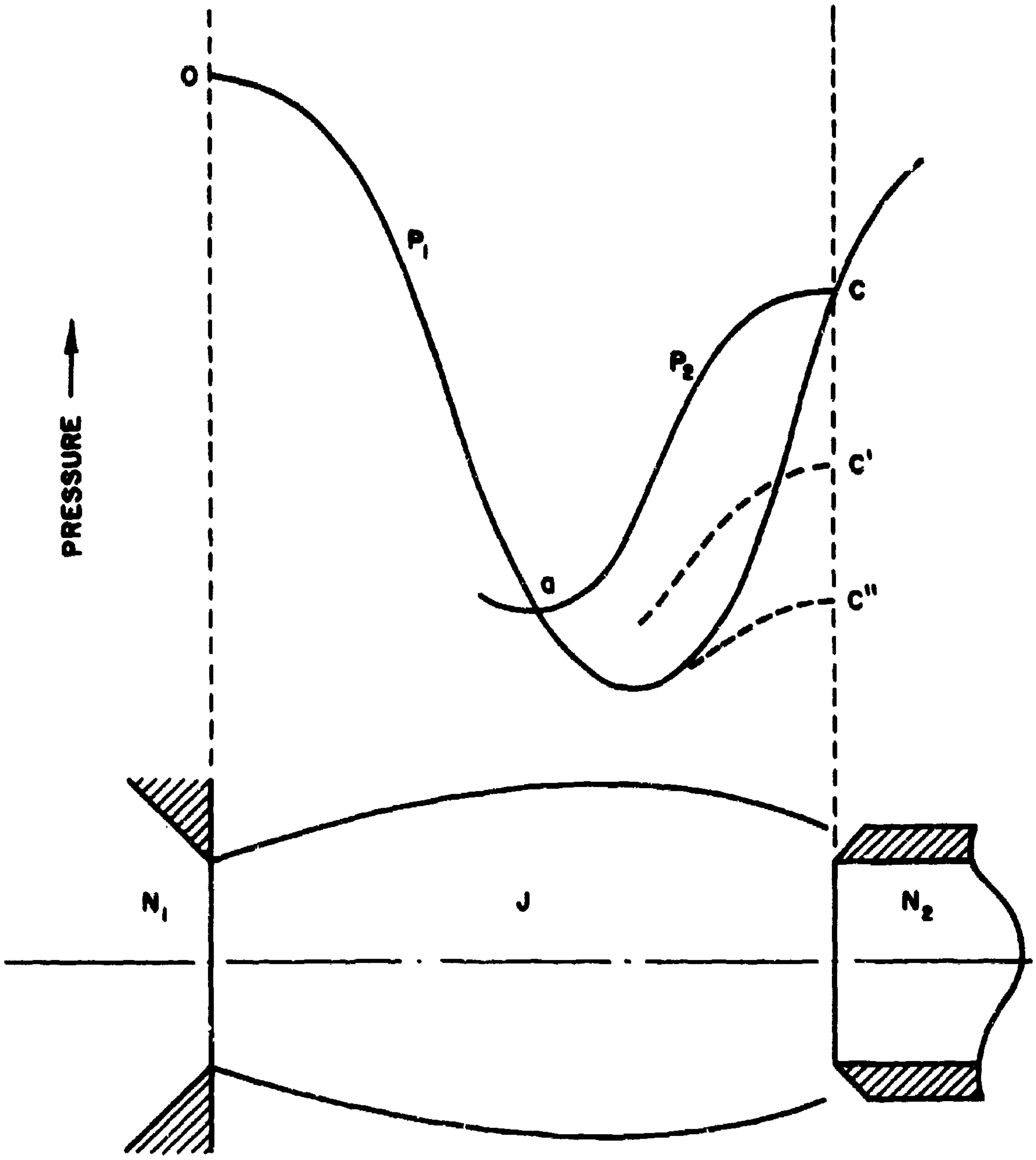


DIAGRAM TO ILLUSTRATE HARTMANN'S POSTULATED MECHANISM

FIGURE 3

the initial suppositions, and several other errors of observation were perpetuated which tended to obscure information that would have led to a better understanding of the mechanism.

Nonetheless, Hartmann laid the groundwork for all subsequent investigations by his painstaking examinations of so many features of the whistle and he was able to indicate the optimum dimensions, working pressures and assembly techniques necessary to obtain the maximum aeroacoustic efficiency. Tests were performed on a wide range of variations of the basic assembly. Among the modifications tested were the use of reflecting surfaces around the nozzles and cavities for intensification of the output; jets and cavities of rectangular or annular section; various nose profiles of the cavities; various ratios of the jet diameters, cavity diameters, resonator lengths and jet-to-orifice separations; synchronization of two whistles, and many other such assemblies. The most successful configuration appeared in the form of the 'stem-jet' (Fig. 2b) where an axial rod runs through the jet stream from the cavity to the nozzle. (This form was discovered independently by Savory[37] and announced at the same time as Hartmann's publication[33], but the former was precluded from making any investigations of the phenomenon due to the extremely small dimensions of his apparatus.) The stem-jet varies in so many ways from the standard Hartmann whistle that several reviews have tended to treat it as a separate class of aerosonic generator. Its output is almost completely independent of the nozzle-to-cavity spacing, neither the amplitude nor the frequency of the whistle changing over wide variations in spacing, and it is completely insensitive to 'intervals of instability' in the jet efflux. Perhaps the most outstanding variation from the Hartmann whistle is the fact that oscillations of the cavity occur for all flows--from extreme high-pressure jets down to low subsonic velocities, and the arrangement makes it possible to keep certain levels of intensity constant while reducing the air consumption by as much as 50%, thus giving an efficiency which is twice that of the best Hartmann whistle. No explanation has yet been offered for this variation from the observed properties of the basic configuration, although it is obvious that the stem acts as a destabilizing device.

Using a Rayleigh disc indicator for measurements of the polar radiation distribution and acoustic power output, Hartmann found that the maximum obtainable aeroacoustic efficiency of the basic form of the whistle was about 6% when the diameter of the cavity was equal to its length. This value decreased with increase in excess pressure past a maximum of 1.5 atmospheres and also optimized at certain nozzle-to-cavity separations.

The Hartmann whistle has attracted the attention of many other experimenters. The main field of interest was the development of a practical aerosonic generator, but certain investigators concerned themselves more with the purely physical problems arising out of the phenomenon--in particular the apparent thermal imbalance, the travelling shock waves in the cavities and the problem of indentifying its mechanism of operation.

Ehret and Hahneman[35] were the first to realize the potentialities of the system and developed a form of the whistle which was used for the ultrasonic testing of alloys. The cavity took the form of a small T-sectioned Helmholtz resonator, the narrow neck directed towards the jet and a membrane forming the back wall from which the oscillations were mechanically coupled to the specimen. This configuration has also been investigated by Kling and Crabol[36] who reported outputs reaching 220 kc/s. Like Ehret and Hahnemann, they also surrounded the jet by an annular reflector which increased the output and gave rise to oscillations of the system with subsonic jets--possibly as a result of the reflector aiding acoustic feedback of vortical instabilities from the cavity orifice to the jet in a similar manner to the mechanism of edge-tone production.

Savory[37] constructed a variety of forms of the whistle and made studies of the effect of introducing de-stabilizing devices into the jet stream ahead of the cavity. These additions included axial rods (the 'stem-jet generator'), annular rings and 'regenerator pads' (small reflectors close to the jet boundary). Each showed a tendency, under certain conditions, to augment the acoustic output and to improve the over-all efficiency.

Palme[38] made stroboscopic shadowgraph studies of the oscillatory external flow which enabled the cycle to be studied in greater detail, and experimented with disc extensions around the jet nozzle and cavity orifice with the object of increasing the acoustic output. He recommended that, for maximum efficiency, the diameter of the cavity should be equal to the widest diameter attained by the cell structure of the jet efflux. Monson and Binder[39] also found that maximum intensities were obtained when the ratio of the cavity diameter to jet diameter was equal to 1.27, values in excess of this giving progressively lower outputs until a value is reached (at approximately 1.60) where the cavity fails to resonate.

Brun and Boucher[11,40,41] directed their research activities toward the development of a high-powered generator for industrial applications. Their 'Multiwhistle' took the form of a group of Hartmann whistles mounted in the throat of a exponential horn and backed by an ancillary resonant cavity. Tests of various ratios of cavity diameter to jet diameter supported the findings of Palme, and Monson and Binder--that when the value of the ratio was in the region of 1.33 it was possible to virtually double the efficiency of the generator, and under optimum operating conditions, efficiencies ranging between 10% and 20% were claimed for the Multiwhistle. Similar claims were made by Kirkin[42,43] for a composite whistle of like configuration. Other experimenters who investigated the general features of Hartmann whistles include White[44], Bugard[45] and le Landais[46]. The work of le Landais is of interest as it represents the first commercial development of the stem-jet whistle as an engineering product and contains a useful review of the properties of this generator. Nomoto[47] mapped the 'regions of instability' of a simple Hartmann whistle for all pressure ratios up to 4.0 and by means of contours of equal loudness was able to display the optimum nozzle-to-cavity spacings for any given working pressure.

Among the few theoretical examinations of the acoustical aspects of the phenomenon is that undertaken by Gravitt[48], who attempted to provide a unified theory for the frequency response of a given resonator. However, he was only able to obtain partial agreement with experimental results due to the adoption of small perturbation theory as the basis of his analysis, with the consequent

omission of significant second-order terms, including those accounting for viscous action and thermal transfer.

A non-acoustic study of the Hartmann whistle was conducted by Thompson[49], assisted by simultaneous studies of flow visualization for the system by Fam[50] and Hartenbaum[51]. The object of this work was to catalog the broad features of the fluid dynamics of the phenomenon in order to compile sufficient data for further studies of the temperature rise in the cavities. Experiments conducted with both fully-expanded and periodic jets showed that the oscillations of the cavity were essentially similar in each case, although minor distinguishing differences were noted for the respective flow phenomena. A large amount of data was compiled by these authors, particularly with respect to movements of the normal shocks within and outside the cavities; however, no tenable theory for the initiation and maintenance of the oscillations was advanced.

A significant theoretical and experimental examination of the Hartmann whistle was recently reported by Mørch[52]. Commencing with a detailed examination of the flow within a periodic jet efflux, Mørch proceeded to investigate the oscillations of the normal shock in front of cavities and blunt bodies, using stroboscopic schlieren techniques. The majority of the experimental work was performed on 'resonators without bore'--i.e., solid blunt bodies having the same silhouette as the resonant cavities. The advantages claimed for this technique were that the stagnation flow was simplified and the amplitude of the oscillations was reduced, thus forming the basis for comparison between small perturbation theory and his experimental data. Mørch also detected weak oscillations of the normal shock at positions where it had hitherto been considered to be stable. This condition he termed 'weak resonance', as opposed to the normal 'strong resonance'. The instability model proposed by this author, based on small perturbation theory, envisages the shock making small oscillations about its position of equilibrium. In this way pressure and velocity perturbations are produced in the region behind the shock and move downstream as plane sound waves; these waves are then reflected at the normal face of the body and move upstream towards the shock through the subsonic stagnation flow. If the perturbation, on arriving at the shock, is in phase with its oscillation resonance

will occur; if not, the movement will be uninfluenced or damped. Thus the shock-to-resonator plane distance will be of major importance in defining the conditions under which resonance occurs. The theory and computations developed from this model are apparently only applicable to weak oscillations near a plane baffle. Substantial modifications, at least, would be necessary to account for the severely non-linear oscillations of a typical cavity--while it can hardly be applied to the case of a Helmholtz resonator where the periodic time is very long.

Thermal Effects in Hartmann Whistle Cavities

The heating effect at the base of a Hartmann whistle cavity has received attention from both experimental and theoretical analysts. Sprenger[19] drew attention to the fact that the temperatures generated within the tubes were very much greater than the free stream stagnation temperature. Using a tube of 10.0 cm length and 0.3 cm diameter which was excited by a spatially periodic jet at a reservoir pressure of five atmospheres, he found that the wall temperature at the closed end reached over 450°C, but erroneously attempted to correlate the mechanism of the phenomenon with that of the Ranque-Hilsh vortex tube. Sprenger noted from observations of a hydraulic analog of the system that a quantity of residual fluid was retained by the tube at its closed end which was subjected to repeated high-amplitude pressure changes during the oscillatory cycle, but did not infer from the hydraulic model that any shock-waves were present within the tube. However, this was suggested to him by oscillograms obtained from a pressure transducer attached to the resonator end-wall, when it was noted that extremely steep-fronted pressure wave-forms were recorded during each compression of the cavity fluid.

Sibulkin and Vrebalovich[53] studied the heating effect using a 10 inch long cavity located within a supersonic wind tunnel and fitted with a destabilizing trip in the form of a ring-airfoil forward of its orifice, with which they detected temperature rises in excess of 150°C. Like Sprenger, they also observed a similar effect occurring at high-speed subsonic flows, provided the trip was present. It was inferred that the dissipative mechanism whereby thermal energy was released was in some way connected with shock wave motions within the cavity. Hartmann had tentatively suggested the existence of such a travelling

wave and it had already been shown that weak periodic shock waves appear under certain conditions when a closed column of gas is forced to oscillate by a sinusoidally-vibrating piston at one end of the column[54,55]. Visual proof of the existence of the internal shock in the Hartmann whistle phenomenon was first provided by Hall and Berry[56] who obtained a series of timed spark-schlieren photographs of a shock wave moving along a 2 inch glass-sided cavity excited by a periodic jet. (This data was construed by Wilson and Resler[57,58] as indicating that steepening pressure waves, rather than non-isentropic shock wave movements, caused the thermal build-up. A theory advanced by them for the mechanism of the heat generation proved to be inconclusive due to the omission of many factors governing the behavior of the gases in the resonator together with an incomplete understanding of the features of the resonant cycle.)

Shapiro[59,60] and Howick and Hughes[61] made limited experimental and theoretical analyses of the thermal energy balance, and, starting from the premise that the heat gain arises as a result of viscous dissipation in the shock wave, attempted to determine the maximum obtainable temperature for a given resonant cavity from estimates of the heat gain from the shock, (the product of the frequency and the total amount of energy dissipated by the shock during one cycle) and the heat loss from the tube walls. The heat lost to the fluid debouched at the end of each cycle was overlooked, but Howick and Hughes, by insulating the walls of a 14 inch long tube, were able to raise the end wall temperature from 450°C to 650°C, showing that the heat loss by conduction to the surrounding air blast was a major cause of the depression of the maximum temperature. It was also surmised by Shapiro that an additional source of thermal energy might arise from the oscillating boundary layers on the tube walls.

Vrebalovich[12] later made extensive tests of the thermal dissipation mechanism, his experimental apparatus being restricted to the case of a resonant cavity located in a supersonic stream. He found that whereas certain blunt-nosed tube profiles required the addition of de-stabilizing trips located upstream of the orifice to initiate and maintain the resonant condition, sharp-lipped tubes would oscillate in the absence of such ancillary equipment. This led him to postulate that the oscillatory cycle was initiated by some flow disturbance (an edge tone at the lip or de-stabilizer, for instance) which caused

the stagnation point of the stagnation streamline to move in an axial direction and thus change the size of the flow separation region which was observed to originate near the lip of the tube. Since this separation region affects the shock shape and the flow field in front of the orifice, Vrebalovich postulated the existence of a feed-back mechanism which might be the cause of a periodic flow disturbance that would maintain the oscillations of the air column. Any pressure disturbance propagated to the base of the tube would be reflected back to the mouth to further upset the stagnation point location and in this way the cavity length would control the resonant frequency. Vrebalovich successfully correlated the many unconnected observations of previous workers to account for the heat gain by the cavity. The thermal build-up was shown, both experimentally and theoretically, to arise from the repeated transit of the tube by a shock wave from which the 'residual fluid' (the proportion of the contained air remaining within the tube for more than one cycle) gained heat by the viscous dissipation process. Consequently the residual fluid will attain a maximum temperature which is limited by heat losses through the tube walls and the mixing process with the non-residual fluid in the cavity. (Tests showed that approximately 90% or more of the initially captured gas is retained in the tube for the following cycle).

From the foregoing digest of the currently available literature relating to the Hartmann whistle and its properties and applications, it is evident that the present state of our understanding of this complicated phenomenon is still incomplete. A brief experimental survey of the features of a typical whistle serves to raise many queries concerning its properties that, to date, have remained unanswered. Typical of the problems yet to be solved is the question of the mechanism whereby the oscillations are initiated and maintained. Why are the 'intervals of instability' separated by regions in which the flow is stable? Why do the oscillations start and cease instantaneously, rather than growing to a maximum and falling off according to some exponential law? How does a de-stabilizing trip aid the generation of oscillations? Is there more than one mechanism whereby oscillations are driven, and if so, are they independent of each other, or are several types of instability phenomena simultaneously in evidence?

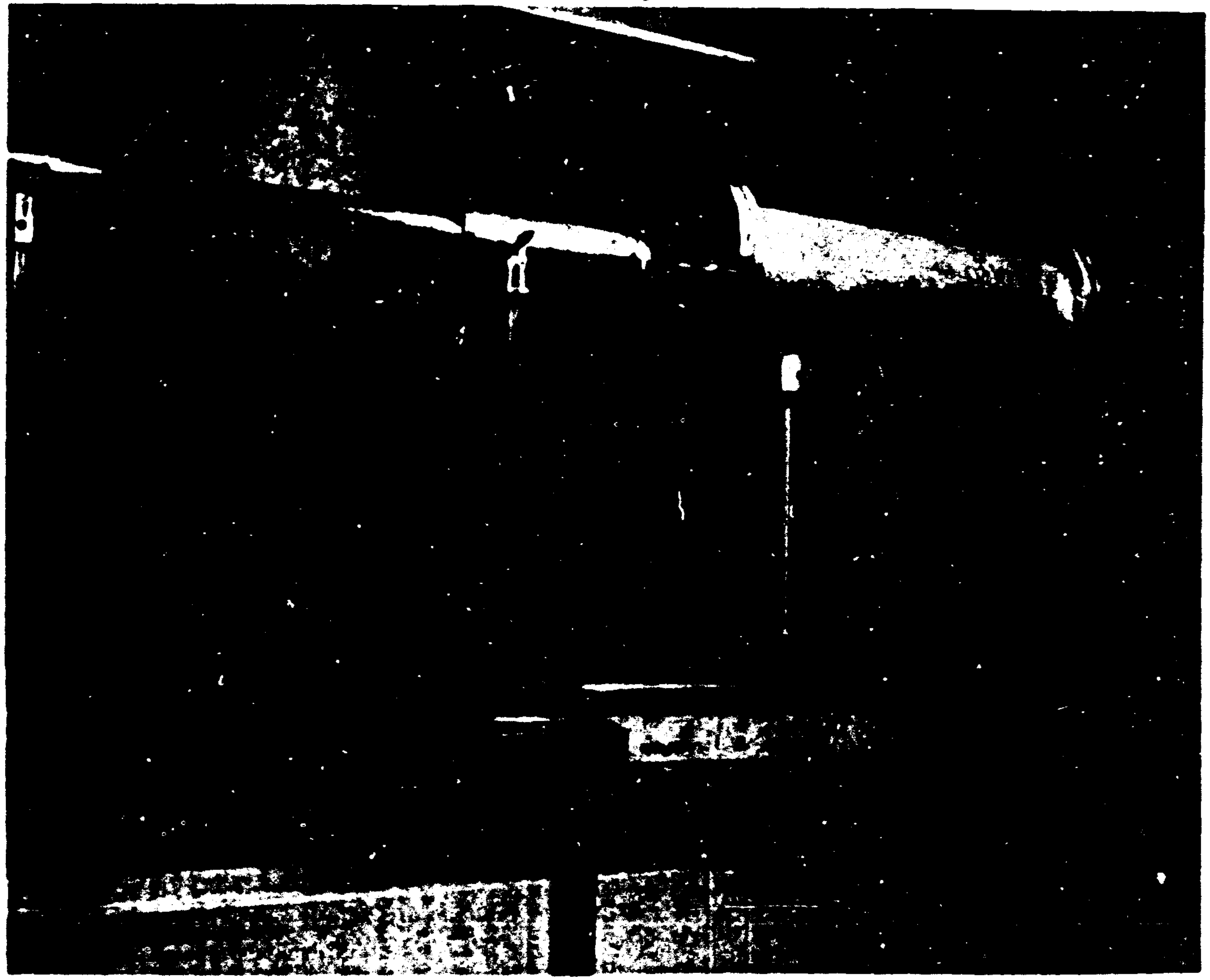
These and other questions will be examined in the remainder of this report, based on experimental investigations of the Hartmann whistle at the Aerosonics Laboratory of the University of California, conducted between August 1961 and August 1964.

EXPERIMENTAL EQUIPMENT

The experimental assembly used for the following investigations of the Hartmann whistle is shown in Fig. 4. A 1.25 in. diameter horizontal air-supply manifold was mounted so that jet nozzles of various types could be screwed into its end, and resonators, clamped to a cross-slide, moved along the jet axis relative to the stationary nozzles. The equipment was constructed in this manner so that a wide combination of nozzles, cavities, pressure-probes, baffles, etc., could be used in conjunction with it, without the need to dissemble or otherwise modify the basic configuration.

The air-supply manifold and the cavities were separated by a distance of 12 ins. from the base-plate in order that the schlieren field should remain unobstructed and so that the base (which was kept small in area) would not reflect acoustic energy back to the flow field which could assist in establishing acoustic feed-back loops for the instability phenomena being investigated. The cavity clamp post was made as slender as possible, while maintaining the required mechanical strength, in order that there should be no undue disturbance of the air flow around it, and was equipped with facilities for adjusting the alignment of the cavity along the jet axis in both the vertical and horizontal planes. The apparatus was connected to the laboratory compressed air supply through a filter and control valve, the air supply being sufficient to maintain an excess pressure of at least 75 lb/in^2 on a 5/16 in. nozzle. A set of calibrated Bourdon pressure gauges, coupled to a pressure tapping in the manifold just upstream of the convergent nozzles, was used to record the jet excess pressures and the nozzle-to-cavity separations were determined from a vernier scale on the cross-slide.

Previous research by Hartmann, et al., has shown that the aeroacoustic efficiency of a Hartmann whistle maximizes when the ratio of the cavity and jet diameters approaches a value of 1.3; and when the cavity length is equal to its diameter. However, since the following investigations were directed towards a



GENERAL VIEW OF EXPERIMENTAL HARTMANN WHISTLE ASSEMBLY AND ANCILLARY EQUIPMENT

FIGURE 4

better understanding of the mechanism of the Hartmann whistle and its properties, the efficiency of the system was of secondary importance and it was decided to keep all cavity and jet diameters equal and to provide for a wide variation in the resonant frequencies of the cavities.

Two characteristic diameters were employed, these being 1/2 in. and 5/16 in. The former, due to its relatively larger scale, was mainly used for optical visualization of the flow variations but was limited by its maximum pressure ratio (with the available air supply) of only 3:1. The smaller diameter system, having a maximum pressure ratio in excess of 6:1, was therefore used for surveys of the acoustical characteristics of the whistle covering wide pressure ranges.

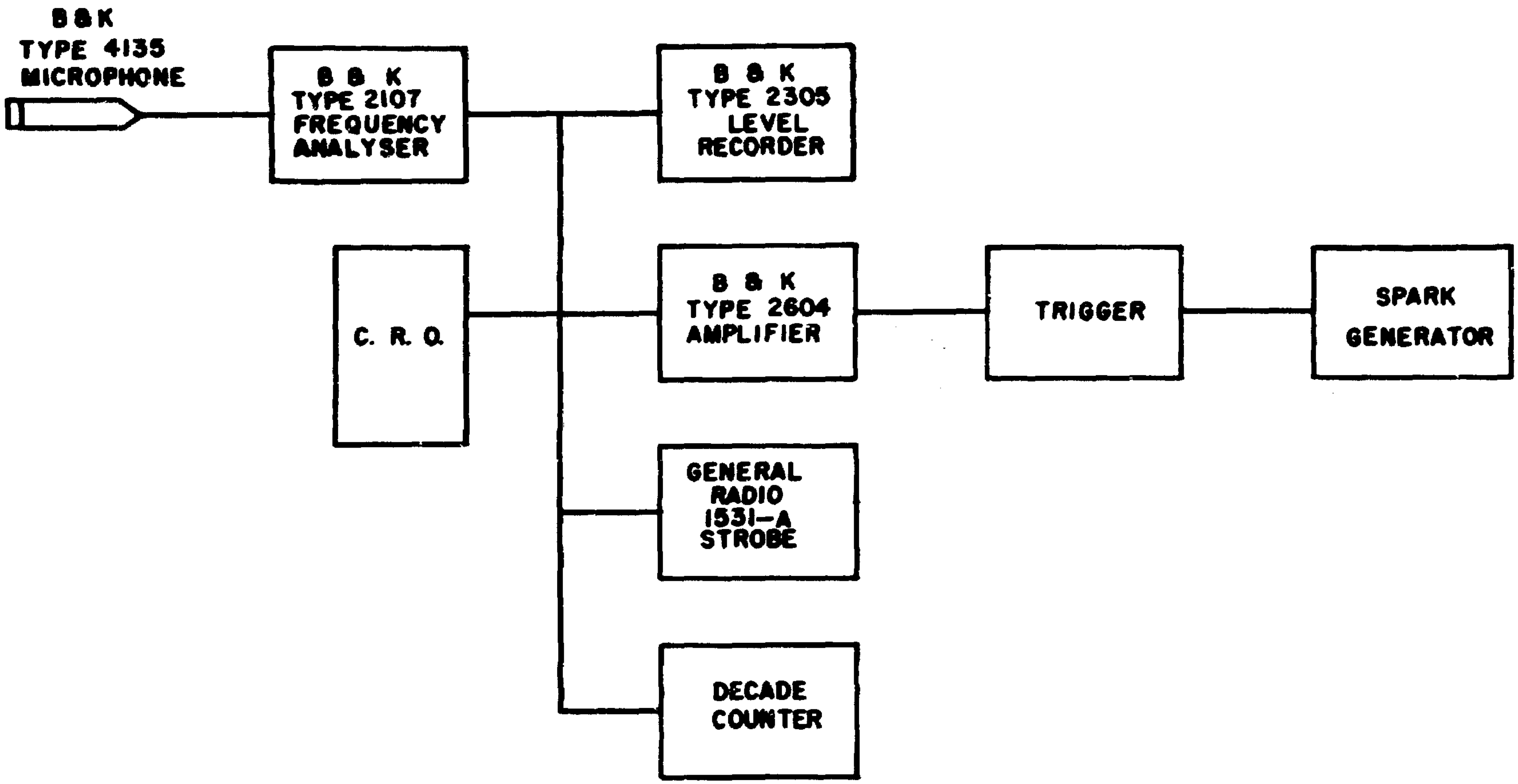
A set of cylindrical cavities ranging in length from 1/2 in. to 16 ins. (the resonant frequencies ranging from approximately 6 kc/s down to 190 c/s) was provided for each jet nozzle. All cavities were constructed with a lip chamfer ranging from 30° to 45° to the axis which ensured that the sonic shoulder of the flow lay at the lip of the tube and not on its outer surface. (Mørch[52] had found that the critical chamfer angle at which the sonic point moves from the cavity lip to the intersection of the chamfer cone and outer cylinder is in the region of 60°.) All cavity pieces and nozzles were made of aluminum and the entire experimental assembly was located in an enclosure equipped with acoustically-absorbant walls which reduced the external sound levels to an acceptable value.

Acoustic measurements of the performance of the whistle were mainly restricted to determinations of the emitted frequencies and the spectral content of the sound. (As noted already, the acoustic power output, the directivity and efficiency were of secondary interest in these tests.) A Brüel and Kjaer Type 4133 standard capacitor microphone, directed toward the cavity orifice, was mounted on a simple linear traverse which made an angle of 135° with the downstream direction of the whistle axis. The motion of the carriage was remotely controlled by a synchronous motor drive so that the microphone location could be continuously varied through a distance of six feet up to cavity lip. Frequency and spectral analyses were obtained from a Brüel and Kjaer Type 2107 frequency analyzer and Type 2305 level recorder, with frequency read-out on a Hewlett-Packard AC-4 decade counter.

Filtered outputs from the analyzing equipment also served to trigger the spark- and strobe-illumination for the optical flow-visualization equipment, as indicated in Fig. 5.

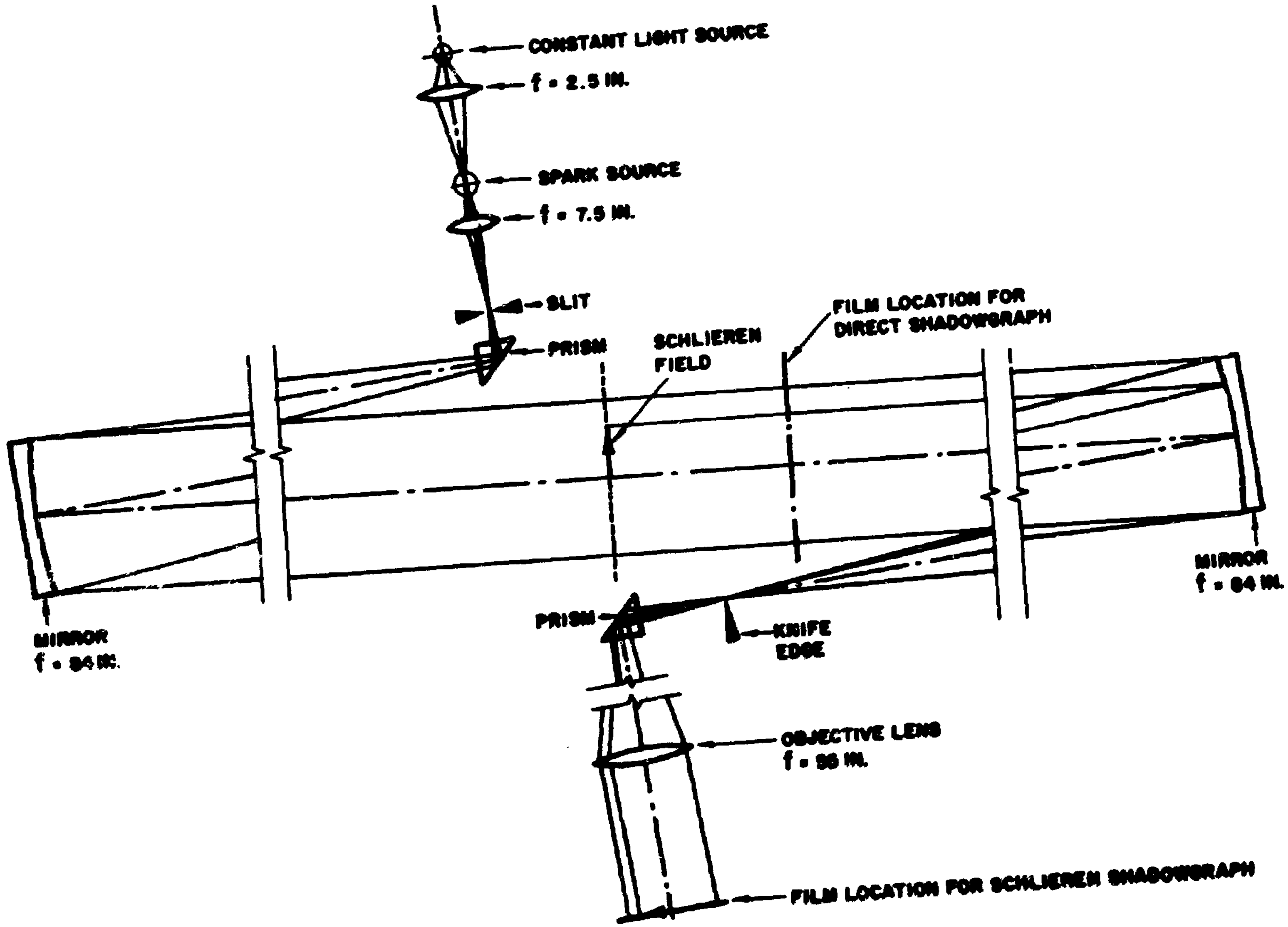
A schlieren-shadowgraph system was assembled for optical studies of the periodic flow variations, using 6 in. diameter parabolic mirrors of 84 ins. focal length and vertical orientation of the source slit and knife-edge. In this way schlieren-shadowgraphs were photographed or projected onto the viewing screen in the normal manner, or direct shadowgraphs obtained by placing a photographic film in the collimated beam at a point behind the apparatus as shown in Fig. 6. Three types of light-source were used. A high-intensity constant source provided by a 500-watt incandescent lamp was used for general observation of the flow-field and for the purposes of aligning the optical equipment. For high-speed photography of the flows the light-source consisted of an 8-mm. spark discharged between magnesium electrodes, having an estimated duration of less than one microsecond and extremely high light intensity. The spark could be triggered at a predetermined instant during the resonant cycle by a suitable electrical pulse derived either from the pressure- or sound-analyzing equipment, or could be fired at arbitrary time by a switch circuit. Phased photographs of periodic flow variations were obtained by triggering the spark from the microphone output. A filtered waveform from the analyzer output was connected to the trigger circuit through a variable-gain amplifier. By increasing the amplifier output until the peak amplitude of the waveform just attained the threshold voltage necessary to trigger the spark, the discharge could be arranged to occur at the same (peak) point in the output waveform, and by moving the microphone through a distance equal to one wavelength of the emitted sound, a series of accurately phased schlieren frames of any regularly periodic sound-emitting flow phenomenon was obtained.

Visual observations of Hartmann whistle oscillations were aided by schlieren-shadowgraph studies using stroboscopic illumination. Replacing the spark electrodes by the xenon flash lamp of a General Radio Type 1531-A 'Strobotac', the flashing rate of which was triggered by a waveform derived from the acoustical output, made it possible to observe in detail any selected phase of the resonant cycle; or the entire cycle could be studied in 'slow motion' by steady movement of the microphone along its traverse.



SCHEMATIC DIAGRAM OF ACOUSTIC ANALYZING EQUIPMENT

FIGURE 5



SCHLIEREN-SHADOWGRAPH ASSEMBLY

FIGURE 6

Several types of films were used for spark-schlieren photography and, because of the short duration of the exposure time, the normal sensitivity rating of the film emulsion was found to be of secondary importance, due to the 'reciprocity-law failure' of the emulsions. Consequently, films with sensitivity ratings ranging from 25 ASA to 700 ASA were used with equal success, and were developed in Kodak DK 50 or Baumann Diafine. Polaroid 'Pola Pan' materials were used where 'single-shot'data were required.

GENERAL SURVEY OF PROPERTIES OF THE HARTMANN WHISTLE

Although several investigators have undertaken surveys of the acoustical properties of the Hartmann whistle, it was found that the available data were surprisingly limited in scope, particularly for resonators having length-to-diameter ratios in excess of 2.0. (Hartmann and most other authors had directed their researches toward the development of ultrasonic generators and hence had used cavities and jets of very small scale). When the cavity diameter is equal to, or exceeds its length--as is generally the case when used for the generation of very high frequencies--the connection between the wavelength of the emitted sound and the small-amplitude 'resonant' cavity length becomes uncertain, due to the magnitude of the correction factors to be incorporated in the latter. Only a limited amount of information was available relating to the frequency responses of long cavities or to the exact relationship between the jet structure and the 'intervals of instability', and for this reason a series of simultaneous schlieren-shadowgraph and acoustic parametric surveys were made to determine the effect of variations in cavity length, jet pressure, nozzle-to-cavity separation, etc., on the output of a Hartmann whistle.

The External Flow

To gain information on the periodic flow variations near the orifice of a oscillating cavity, phased shadowgraphs were taken at selected intervals during the resonance cycle, using the spark-triggering technique described in the previous section. For the purposes of this test a 2 in. long cavity of 0.5 in. diameter was located 0.58 in. from a 0.5 in. nozzle in one of the

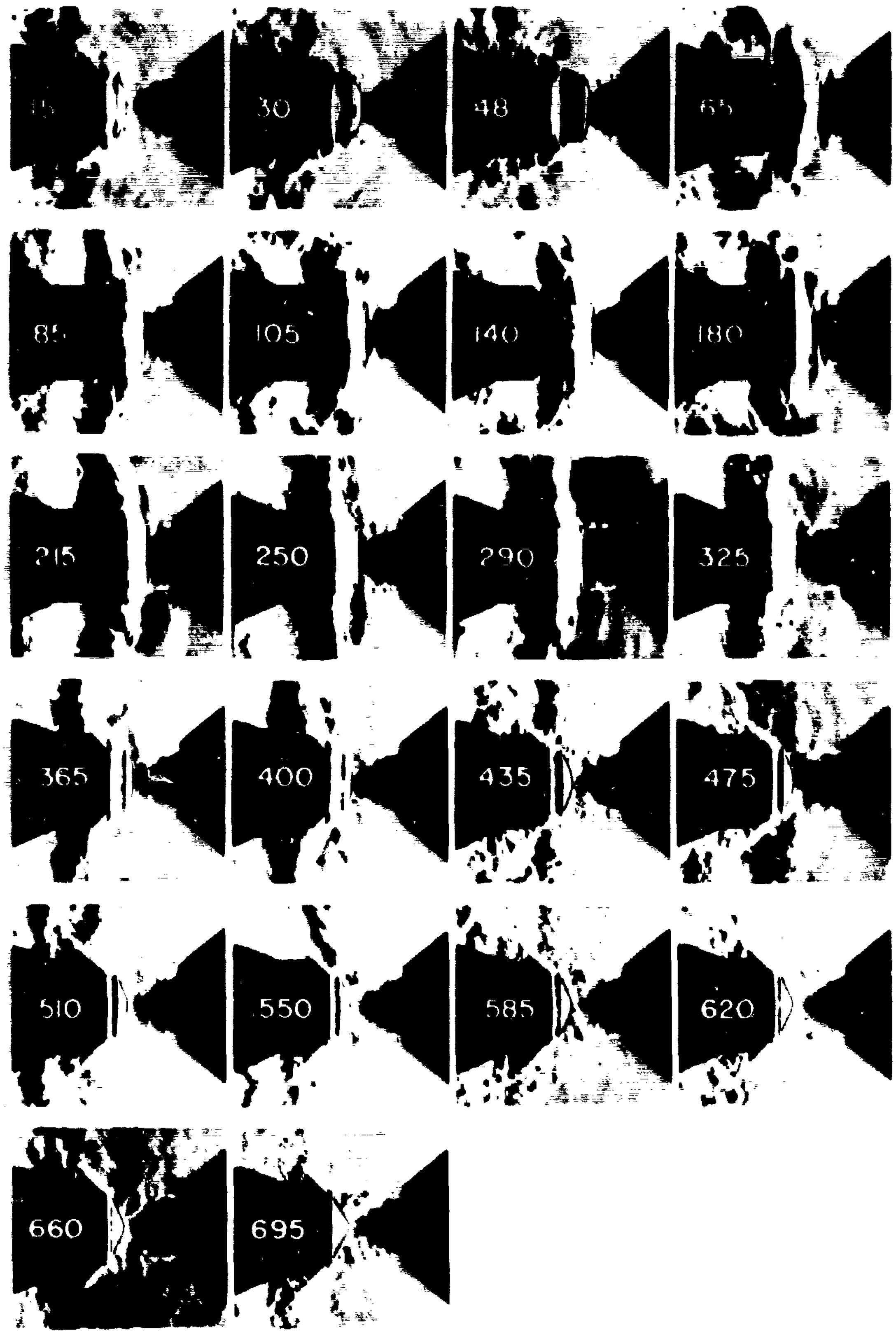
unstable zones, where it oscillated at its first harmonic frequency of 1,413 c/s when excited by a periodic jet of 35 lbs/in^2 excess pressure. Fig. 7 illustrates the flow variations recorded at regular intervals throughout the cycle. The frames, arranged in chronological order, were taken at approximately 37 microsecond intervals by half-inch movements of the microphone traverse. The computed elapsed time, in microseconds, from the emission of the pressure wave is shown on each frame and may be considered accurate to within $\pm$ 5 microseconds of the value stated. The main features of this study can be summarized as follows:

1. Mass-flow variations. The cavity charges with fluid from the jet for approximately half of the cycle and then debouches, there being evidence of powerful vorticity developing during the discharge.

2. Detached shock instability. The normal shock-disc separating the supersonic flow from the separation region oscillates with large amplitude in an axial direction, with periodic distortion of its normal (stable) shape. The motion of the shock is plotted in Fig. 8.

3. Acoustic output. The large mass-flow variations at the cavity orifice gives rise to high-intensity acoustic radiation which is characterized by a periodic waveform having a fast rise-time and of similar shape to the graph of the axial movements of the shock. In consequence the emitted sound is rich in odd- and even-numbered harmonic frequency components. The steepfronted out-going pressure wave is visible in the first three frames of Fig. 7.

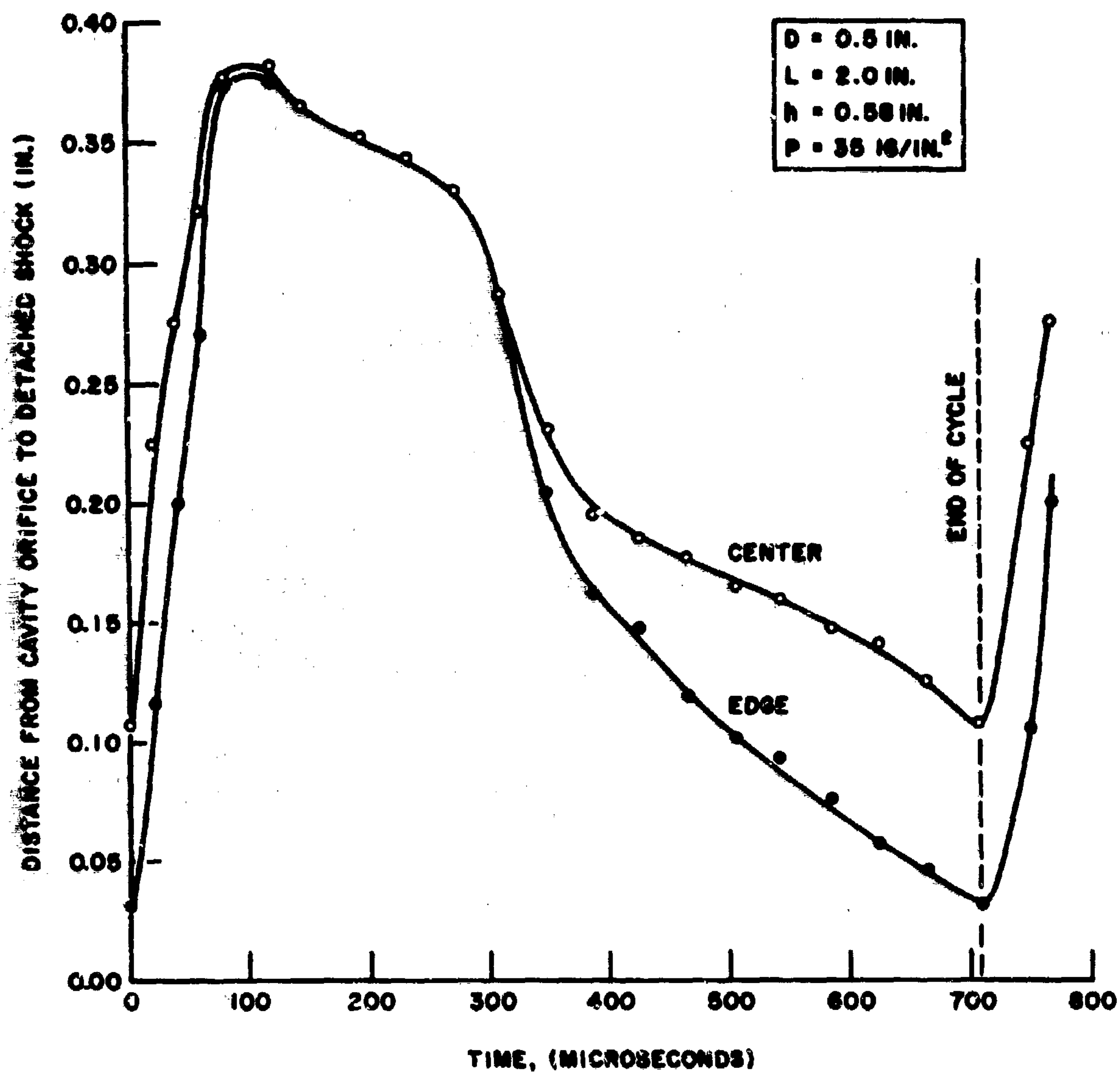
An estimate of the fluctuating pressure at the closed end of the cavity was obtained by replacing the end cap by one containing a small orifice (Fig. 9). A periodic jet issued from this perforation during part of the resonant cycle, and the dimensions of its cell structure gave an indication of the pressure within the tube at a given time. Typical orifice flows are shown for various phases of the cycle in Fig. 9. From measurement of the lengths of the first cell of the emergent jet, values of the



SERIES OF PHASED SPARK-SCHLIEREN SHADOWGRAPHS OF 0.5 IN. HARTMANN WHISTLE RESONATING AT ITS FIRST HARMONIC FREQUENCY

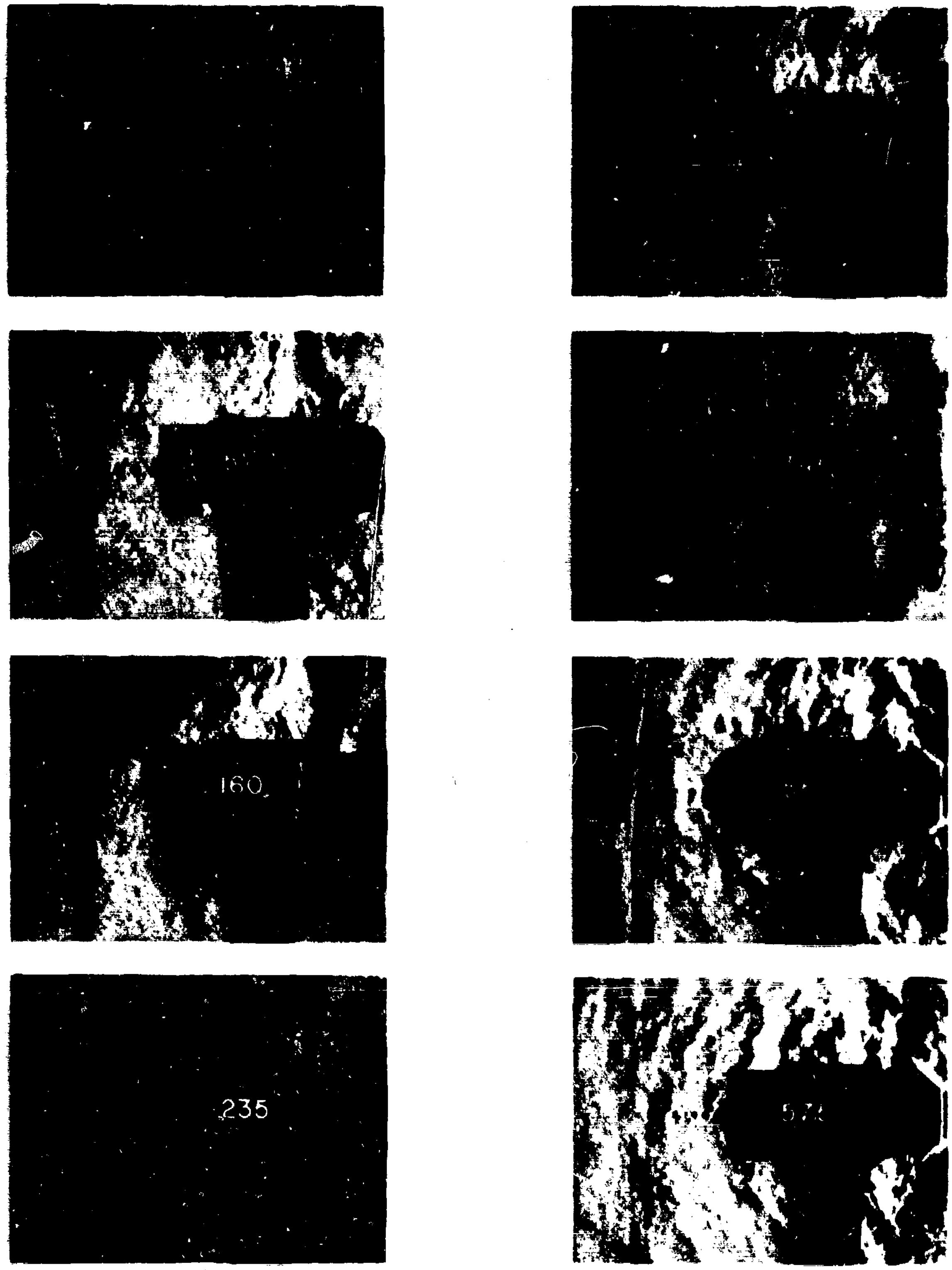
$L = 2.0$ in, $P = 35$ lb/in^2, $h = 0.58$ in, $f = 1413$ c/s

FIGURE 7



OSCILLATION OF DETACHED SHOCK DISC OF RESONATING HARTMANN WHISTLE CAVITY

FIGURE 8



SPARK-SCHLIEREN SHADOWGRAPHS OF THE VARIABLE-PRESSURE PERIODIC JET EMERGING FROM THE END-WALL PERFORATION OF AN OSCILLATING 0.5 IN. HARTMANN WHISTLE CAVITY

$L = 2.0$ in, $P = 35$ lb/in^2, $h = 0.58$ in, $f = 1413$ c/s

FIGURE 9

generating pressure were derived from the empirical formula developed by Hartmann:

$$\frac{S_1}{D} = 0.30 + 0.98\sqrt{\frac{P_o - 1.96}{1.033}}$$

where S_1 is the length of the first cell, D is the nozzle diameter and P_o the absolute pressure of the jet in kg/cm^2, for cell aspect ratios greater than unity.

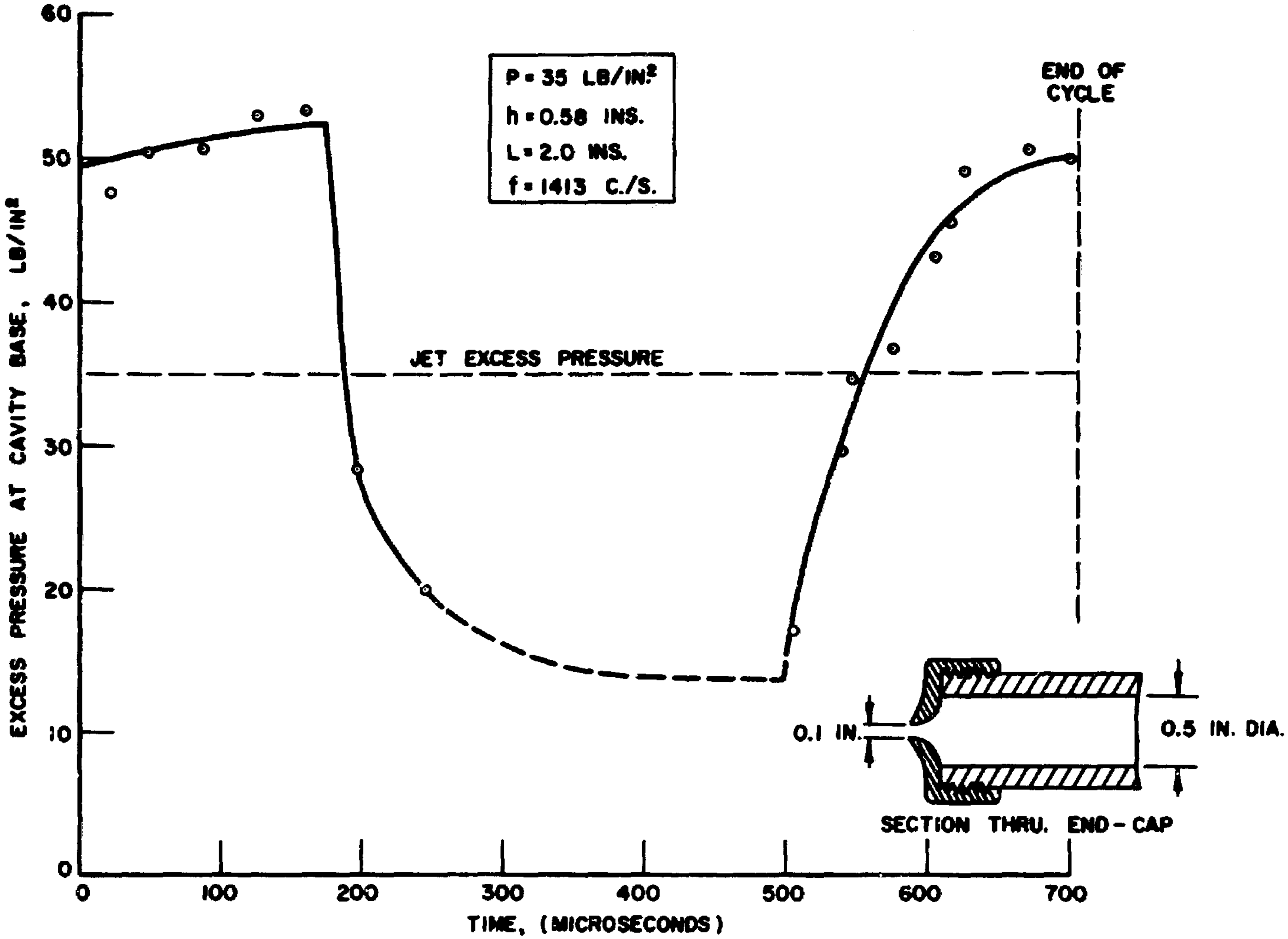
The pressure variation at the closed end of the cavity is displayed in Fig. 10. These values are only approximate since no correction was incorporated in the above expression to account for the pressure reduction due to the fluid loss from the rear of the cavity, but comparison with data obtained by other authors[12,49,59] using different measuring techniques shows a close agreement, both with the values of pressure plotted and the shape of the curve.

The Internal Flow

The foregoing observations of fluctuating pressure at the cavity base, together with other studies of the phenomenon by various authors (reported in the Introduction) tended to indicate a possible connection between the travelling shock within the tube and the mechanism of the whistle.

To establish the relationship between variations in the internal and external flows, square-section transparent-sided cavities were constructed in which the cyclic phenomena at the orifices and along the entire length of the tubes were simultaneously in evidence.* These cavities consisted of 3/8 in. wide channels cut in 3/8 in. aluminum plates which were sandwiched between two optically-flat glass windows, the assemblies being made gas-tight by rubber-strip seals. Thus the entire length of the tubes up to their

*It was found that a fully two-dimensional system, enclosing the nozzle, jet flow and cavity between two glass plates, would not oscillate under any combination of circumstances in the absence of an added tripping mechanism, and even placing a flat surface close to the jet boundary of the normal axially symmetric configuration was sufficient to damp all oscillations.



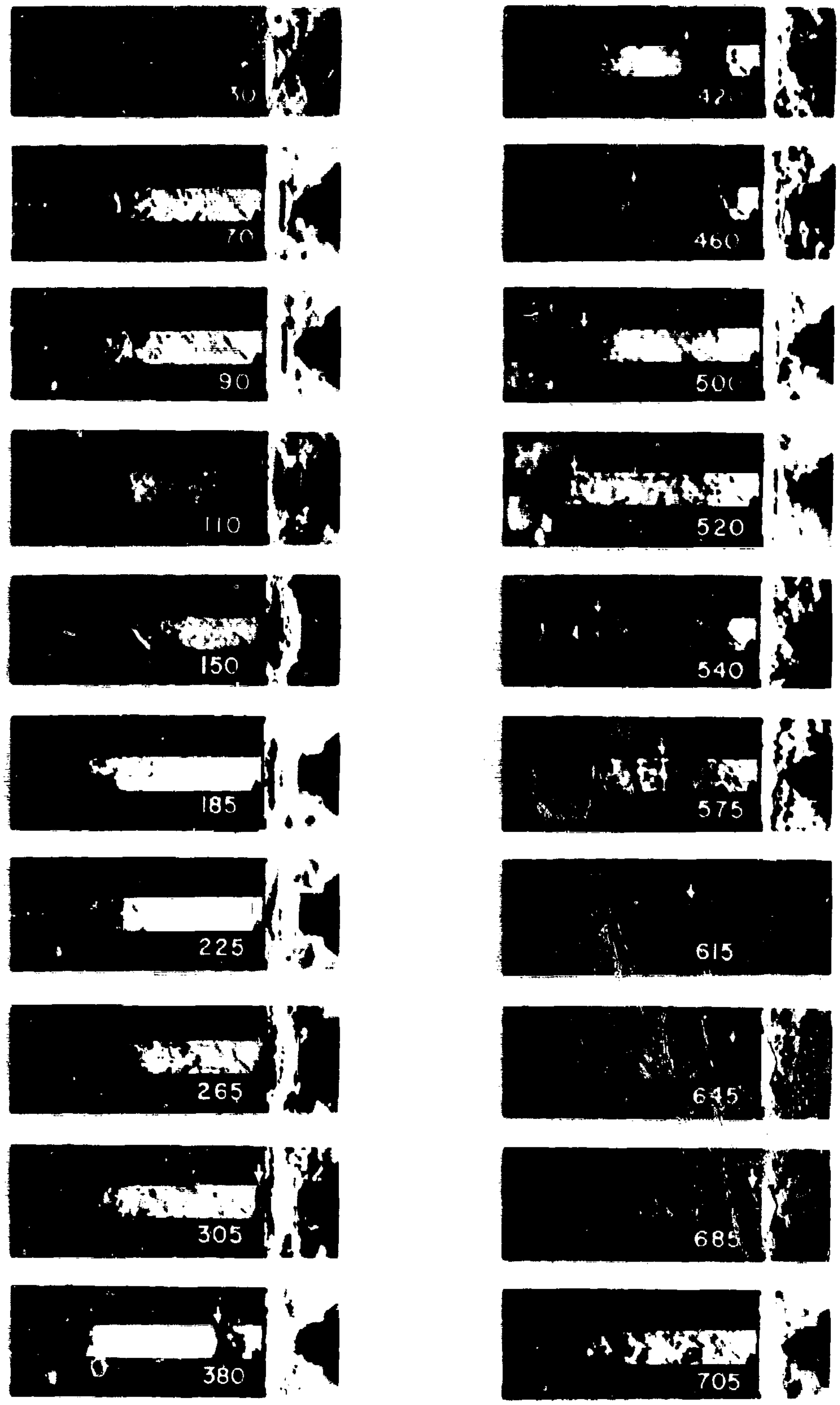
PRESSURE VARIATIONS AT CAVITY BASE

FIGURE 10

exists could be viewed in the schlieren field. The cavities so formed could be excited by either the 5/16 in. or the 3/8 in. jet--the latter being chosen because of its proportionately larger scale and clarity of the external flow features.

The previously noted variations in the separation flow and the jet emerging from the rear perforation were connected to the movement of the internal shock with the aid of a 2-inch transparent-sided cavity which had a small orifice drilled out in its thin end-wall. The events of one cycle during resonance of this cavity are displayed in Fig. 11, where the geometrical and flow parameters remain the same as for Figs. 7 and 9. (The change in the cross-sectional shape of the cavity orifice resulted in a small shift of the resonant frequency from 1,413 to 1,430 c/s.) The motion of the internal shock is easily discernable and its displacement as a function of the periodic time is shown in Fig. 12, where the movement of the detached shock disc is also displayed. The velocity of the internal shock relative to the tube is more or less constant at about 87.5% of sonic speed--a feature that has been borne out by similar tests on longer channels.

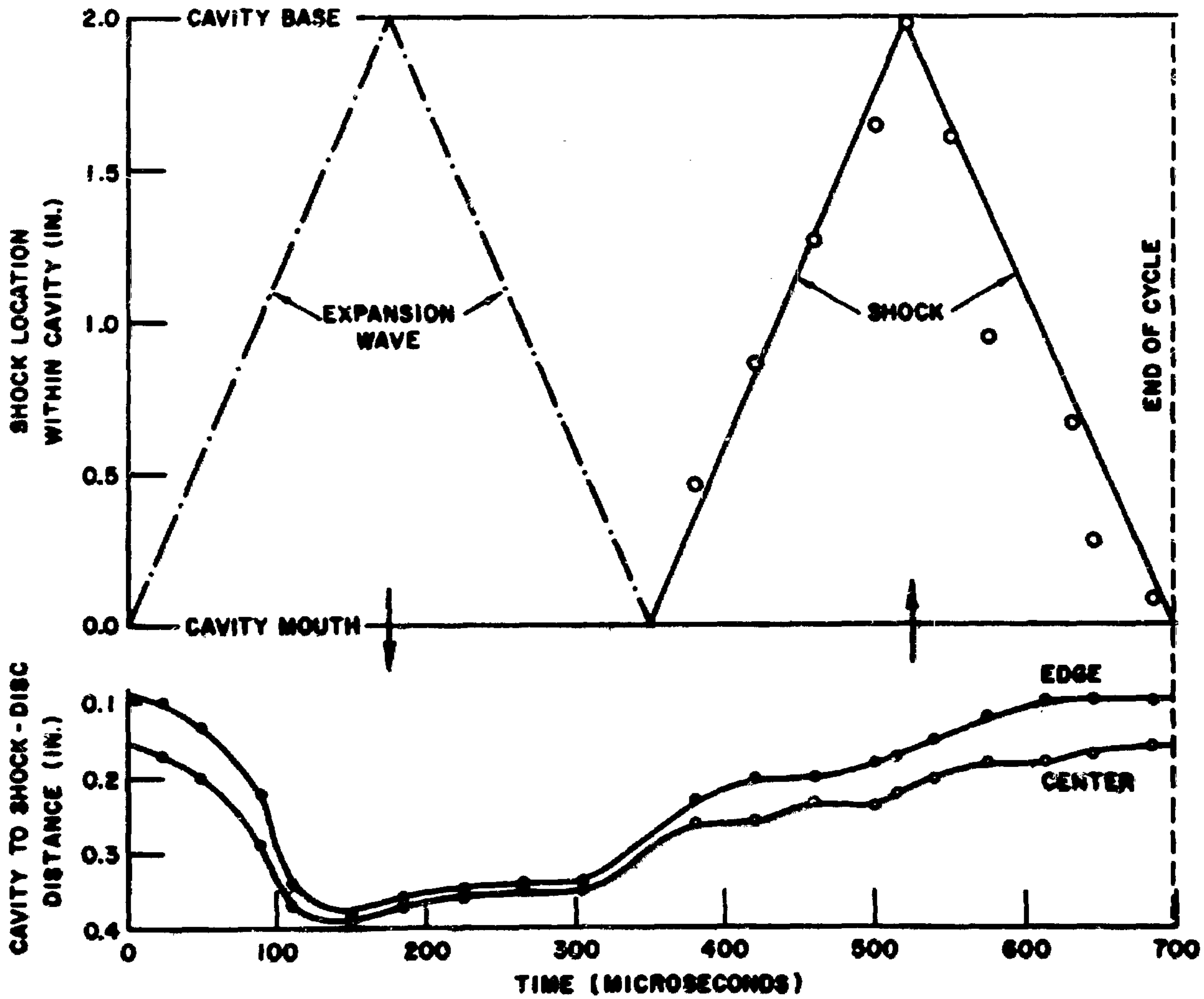
The main features of the resonance of a rectilinear cavity excited by a periodic jet may be assembled from the foregoing three optical surveys, illustrated in Figs. 7, 9 and 11. The cycle may be considered to commence at the time when the radiated pressure wave originates at the cavity orifice, that is to say, as the debouchment commences. At this instant the pressure at the cavity base is near a maximum but falls rapidly as fluid is expelled. The external detached shock which separates the supersonic jet flow from the stagnation flow at the orifice moves upstream with high velocity as debouchment commences as the powerful radiated pressure wave is initiated. The shockwave remains at this outer position as the cavity debouches until, as the emergent mass-flow rate falls off, it eventually moves back to its original location. At approximately the half-periodic time the debouchement ceases and fluid commences to flow into the cavity, accompanied by a travelling shock wave which transits the tube at near-sonic velocity. Arrival of the shock at the end wall causes a vortex ring to be emitted from the perforation in it, with the development of a periodic jet due to the high pressure attained at the cavity base. (Note that vortex ring is also formed within the



PHASED SPARK-SCHLIEREN SHADOWGRAPHS OF THE OSCILLATION OF A 0.375 IN. TRANSPARENT-WALLED HARTMANN WHISTLE CAVITY

$D = 0.5$ in, $L = 2.0$ in, $P = 35$ lb/in^2, $h = 0.58$ in, $f = 1430$ c/s

FIGURE 11



VARIATIONS OF LOCATIONS OF INTERNAL AND EXTERNAL SHOCKS DURING COURSE OF ONE CYCLE

FIGURE 12

cavity at the same instant.) The shock, on reflection from the end of the cavity, arrives at the orifice to complete the cycle and the cavity again debouches. Presumably an expansion fan transits to tube during debouchement, initiated by reflection of the internal shock at the open end as indicated in Fig. 12.

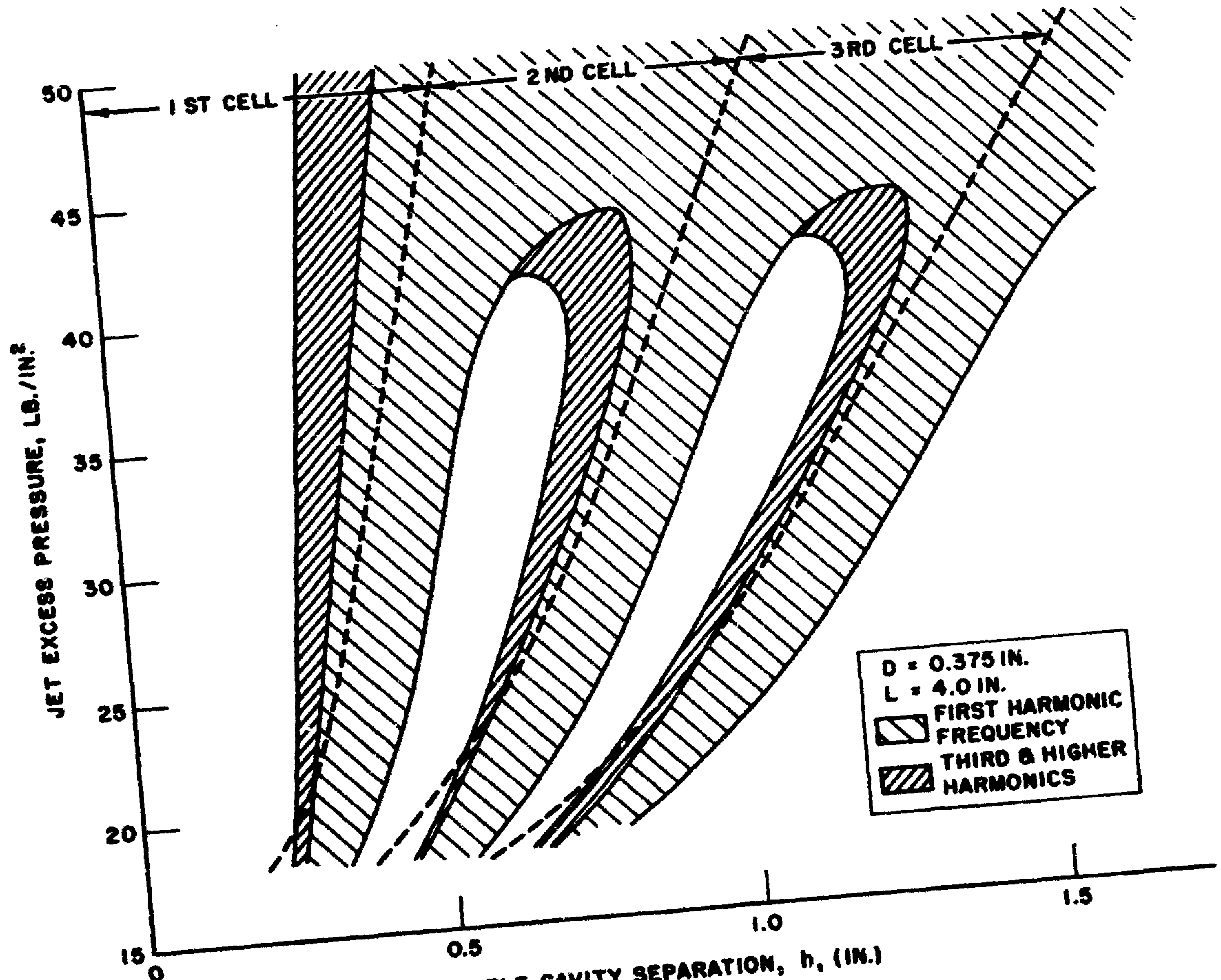
Frequency Response of the Hartmann Whistle

Variations of the acoustic output of the whistle with changes in jet pressure, cavity location, etc., were noted by Hartmann during his initial studies of the phenomenon. He drew attention to the connections between the geometry of the efflux cell-structure and the cavity locations where the flow changed from the stable (non-resonant) to the unstable (resonant) condition, and named these zones the 'intervals of instability'. He also determined the wavelengths of the emitted sound over a limited range of distances and cavity dimensions (having lengths more-or-less equal to their diameters in the range 2 - 10 mm) as the jet-to-cavity separation was varied, but major deviations from the natural resonant frequencies occurred because of the extreme non-linearity of the oscillations. As a result it was erroneously assumed that throughout the first and subsequent instable zones the wavelength varied as a linear function of the cavity location, the frequency falling as the spacing increased. Tests on longer cavities would have shown this to be incorrect but, apart from these surveys, no other detailed investigation of the variations of the sound of a Hartmann whistle has been reported.

In order to extend the range of the studies referred to above, the following measurements were made of the frequency response, which relate the acoustic output of a typical cavity to the jet pressure (and hence to the jet structure) over the first three jet cells. It was found that all cavities having lengths in excess of five diameters behave in essentially the same way--high harmonic frequencies being driven at the upstream end of each instable zone and the first harmonic over the downstream and longer part. Minor variations of their responses are attributable to differences in the ratios of jet to cavity diameters, the cavity lengths and cross-sectional shapes, the shape of the cavity lips or, in general, to variations in the Q-factors of the resonators.

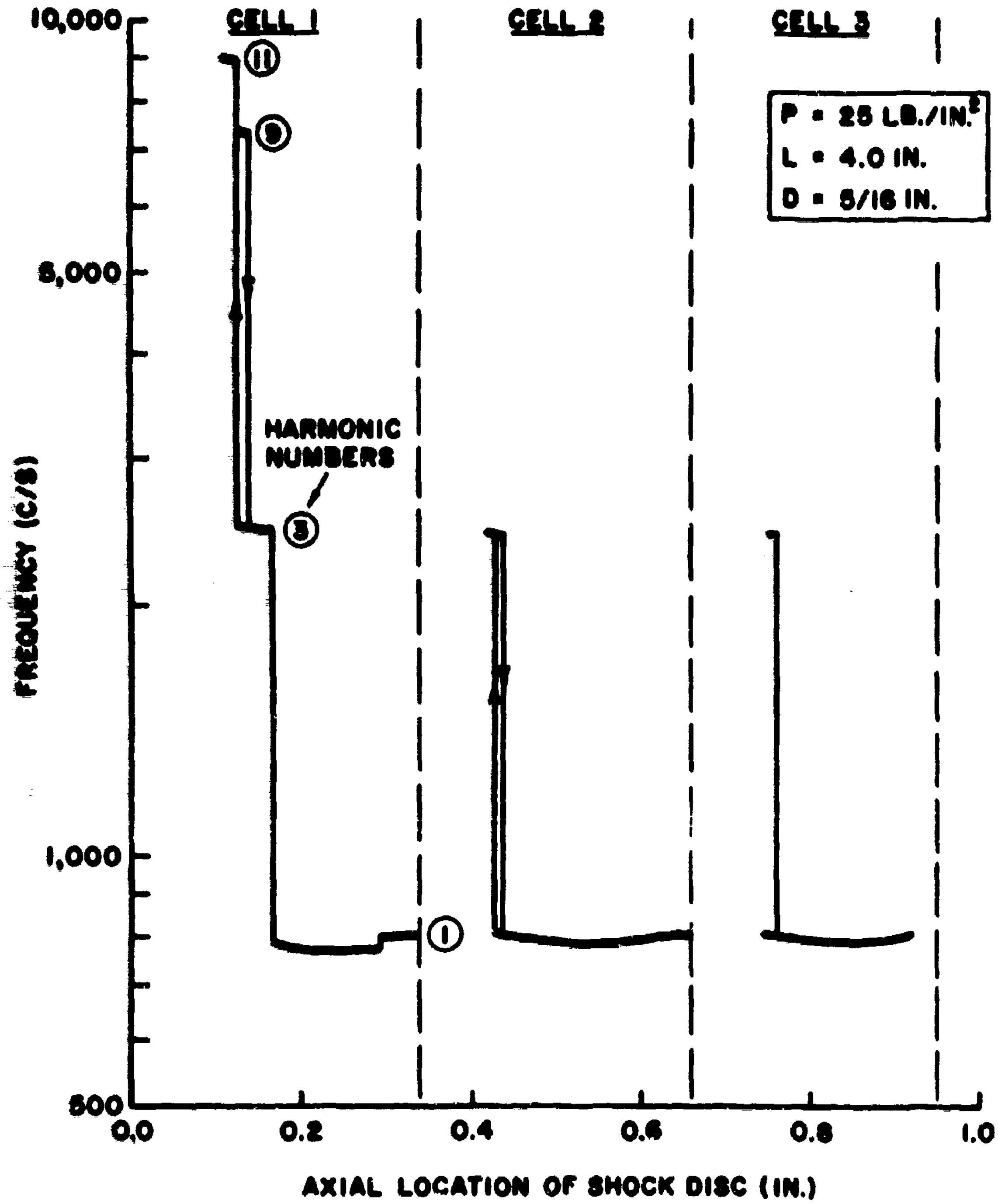
A survey of the limits of the unstable zones, similar to work by Nomoto[47], is displayed in Fig. 13, where the locations at which a 4-inch cavity resonated when excited by a 5/16 in. jet are plotted as a function of the jet pressure. It will be noted that, for jet pressures in excess of 43 lb/in^2, the cavity resonated at all positions downstream of the initial stable zone. For lower pressures, down to approximately 25 lb/in^2, the unstable zones were centered on, or crossed the cell boundaries, but below this jet pressure the zones lay entirely within the cell limits. Further investigations showed that the apparent shift of the unstable zones relative to the jet geometry was due to the fact that the significant characteristic dimension defining their location was not so much the nozzle-to-cavity spacing but rather the position of the detached shock along the jet efflux. It was noted that, as the cavity (and hence its associated shock-disc) was slowly moved away from the nozzle, the shock became unstable and commenced to oscillate near the apex of each expansion cone in the jet efflux and ceased oscillating when it approached the end of each cell. Therefore, the frequency responses of the 4-inch cavity in the unstable zones are plotted in Figs. 14a to 14f as a function of the detached shock location, for jet pressures ranging from 20 to 50 lb/in^2. The difference between the nozzle-to-cavity spacing and that from the nozzle to the centre of the shock disc (being the width of the stagnation flow, or 'stand-off distance') was determined from observations of a stable detached shock in front of a blunt body of the same external profile as that of the cavity body. The stand-off distance were found to remain constant as the blunt body was moved along the periodic jets, but minor variations occurred as the jet pressure was increased, the largest separation distances being recorded for the lowest jet pressures.

Examination of Figs. 14a to 14f indicates that, for all jet pressures less than approximately 40 lb/in^2, the jet effluxes have a regular spatial periodicity, and basically the same cavity frequency response is repeated over each successive cell-length. Jet pressures in the range from 40 to 43 lb/in^2 represents a transition condition (Fig. 14d) and over 43 lb/in^2 the spatial periodicity breaks down and the first harmonic frequency of the cavity is driven at all points along the jet stream.



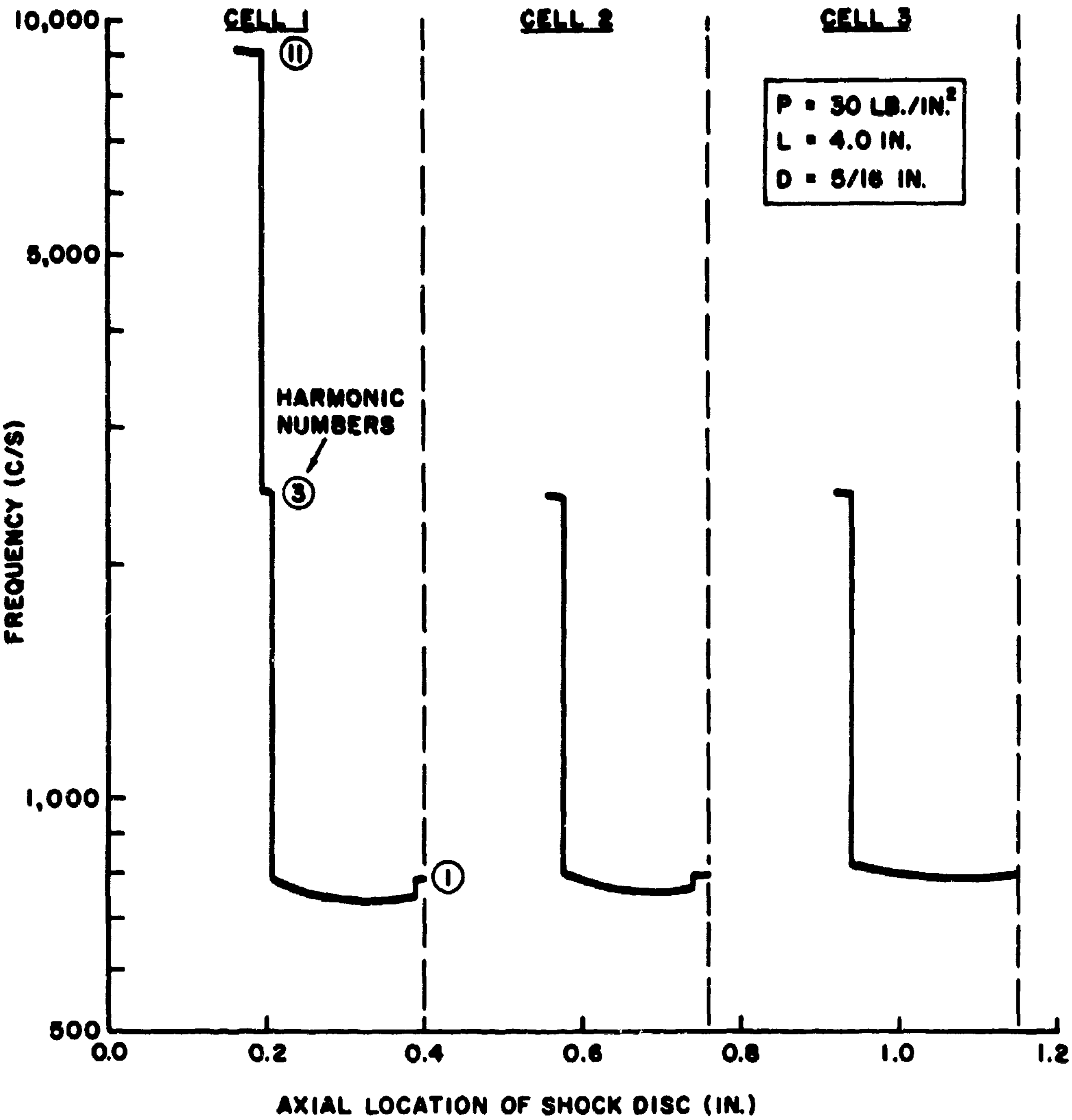
VARIATIONS IN OUTPUT OF A HARTMANN WHISTLE

FIGURE 13



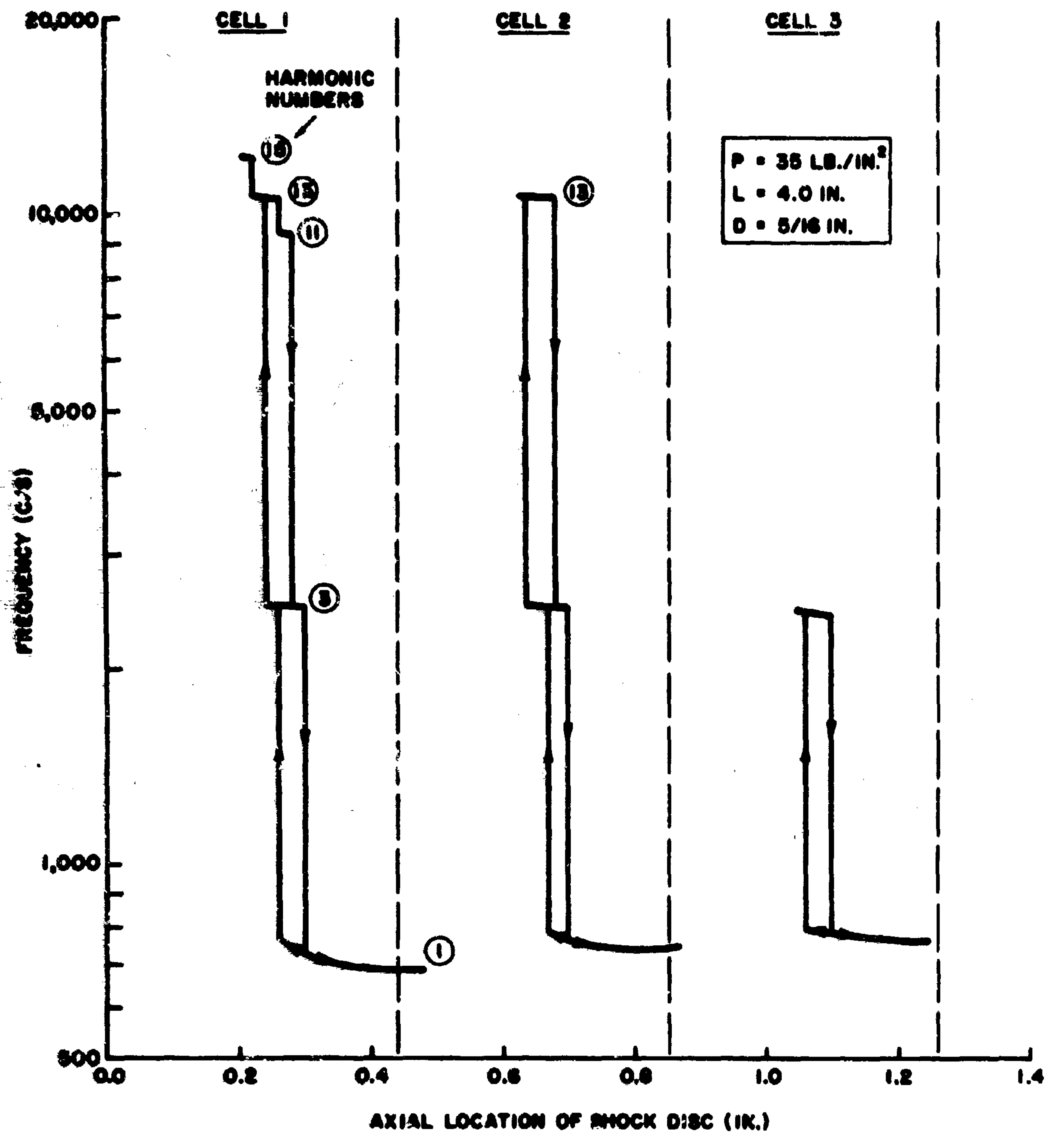
FREQUENCY RESPONSE OF A HARTMANN WHISTLE

FIGURE 14a



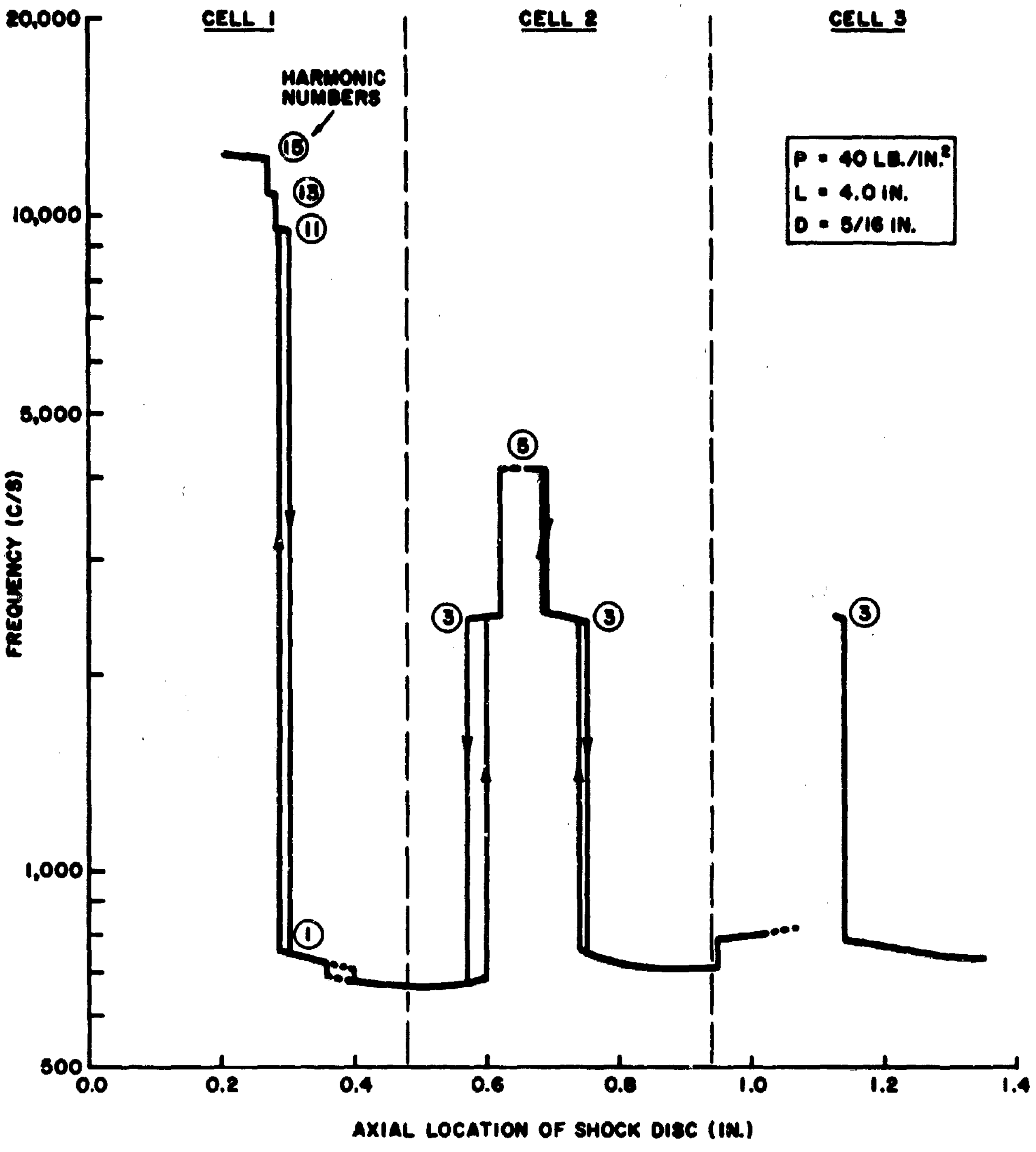
FREQUENCY RESPONSE OF A HARTMANN WHISTLE

FIGURE 14b



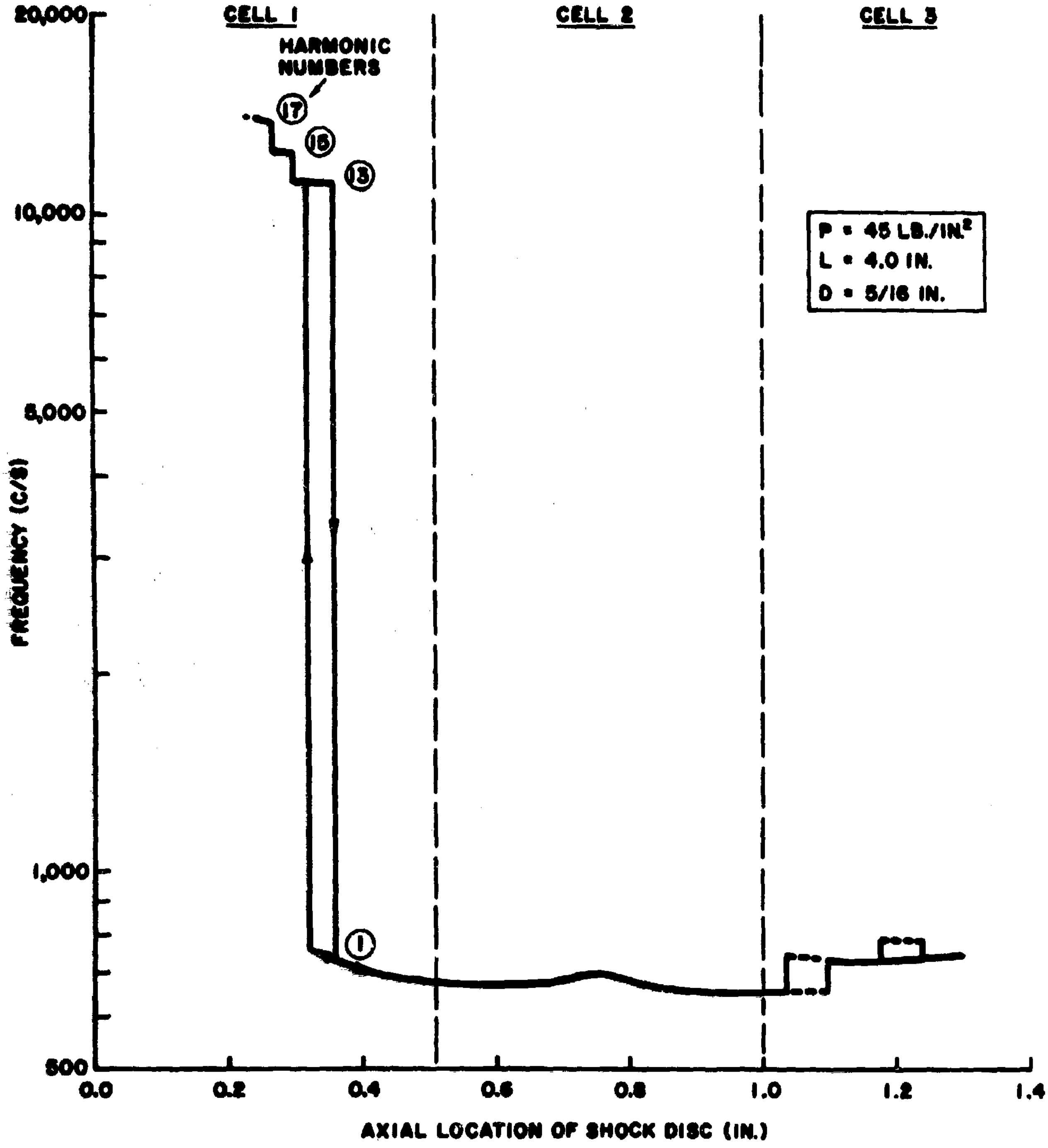
FREQUENCY RESPONSE OF A HARTMANN WHISTLE

FIGURE 14c



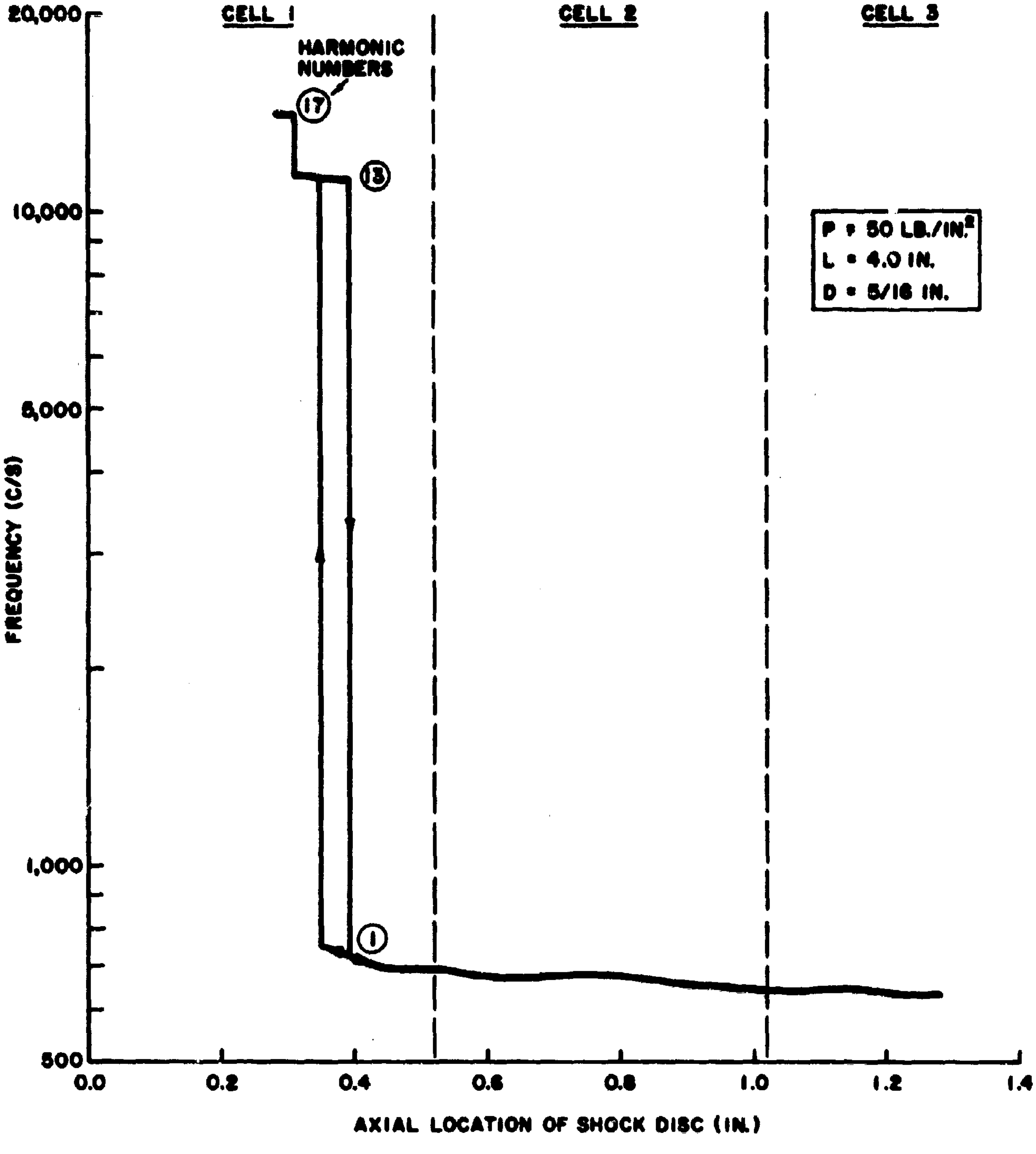
FREQUENCY RESPONSE OF A HARTMANN WHISTLE

FIGURE 14d



FREQUENCY RESPONSE OF A HARTMANN WHISTLE

FIGURE 14e



FREQUENCY RESPONSE OF A HARTMANN WHISTLE

FIGURE 14f

For strictly periodic jets having nozzle pressures ranging from 15 to 40 lb/in^2, the frequency responses show several common features. Over the initial part of each cell very high harmonics may be driven; in some cases the fifteenth, or higher, having been identified. (Since the rectilinear cavities used here correspond to 'quarter-wave tubes' only the odd-numbered harmonic resonant frequencies could be driven, but spectral analyses of the radiated sound have shown that it was very rich in all component frequencies, odd- and even-numbered harmonics to the sixteenth, and higher, having been detected.) As the nozzle-to-cavity spacing was increased the output frequency dropped to lower harmonics and eventually to the fundamental, which was driven over the major portion of each cell-length. These resonant frequencies varied from the normal (small-perturbation) frequencies of the cavities by as much as 10%. Several of the response curves show that a hysteresis condition exists in the regions of the jumps from one harmonic to the next, with a resonating cavity tending to remain at its driven frequency as its location is changed; and, when its mode of oscillation ultimately changes to the next driven frequency, it remains in this condition, even when moved back to its original location.

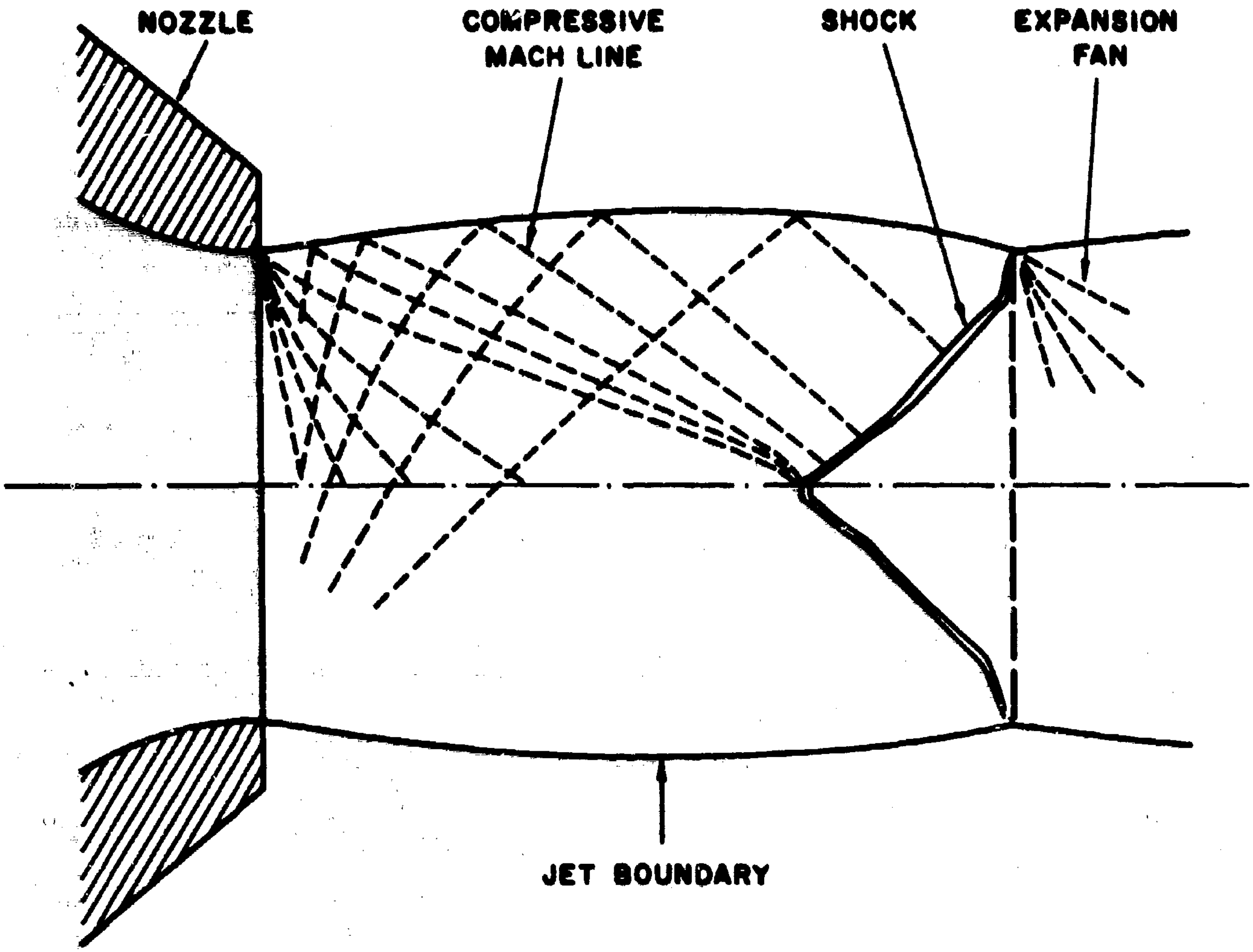
No detailed analyses of the acoustic power output were undertaken in conjunction with this frequency survey since a report by Hartmann[29] has indicated that the sound field has pronounced directionality. Preliminary measurements, using the system described above, showed that there were major changes in the radiated sound distribution patterns of the whistle when the resonant frequency changed from a given mode of oscillation to the adjacent harmonic. Hence any analyses of the radiated power would have involved integrating the sound pressure levels recorded over a circumferential traverse of the far sound field of the whistles in order to provide meaningful information relating to their acoustic powers. However, data from a microphone at a fixed station indicated that the maximum sound pressure levels were developed near the mid-points of the first harmonic frequency distributions for periodic jet effluxes.

The above frequency analyses indicated that a further study of the jet structure was required in order to relate the variations noted to a general mechanism for the initiation and maintenance of the oscillations. It was necessary to account for the fact that the first harmonic frequency was only driven over the downstream sections of the cells of strictly periodic jets, and the nature of the breakdown in spatial periodicity at pressures in excess of 43 lb/in^2.

The Structure of Periodic Jets

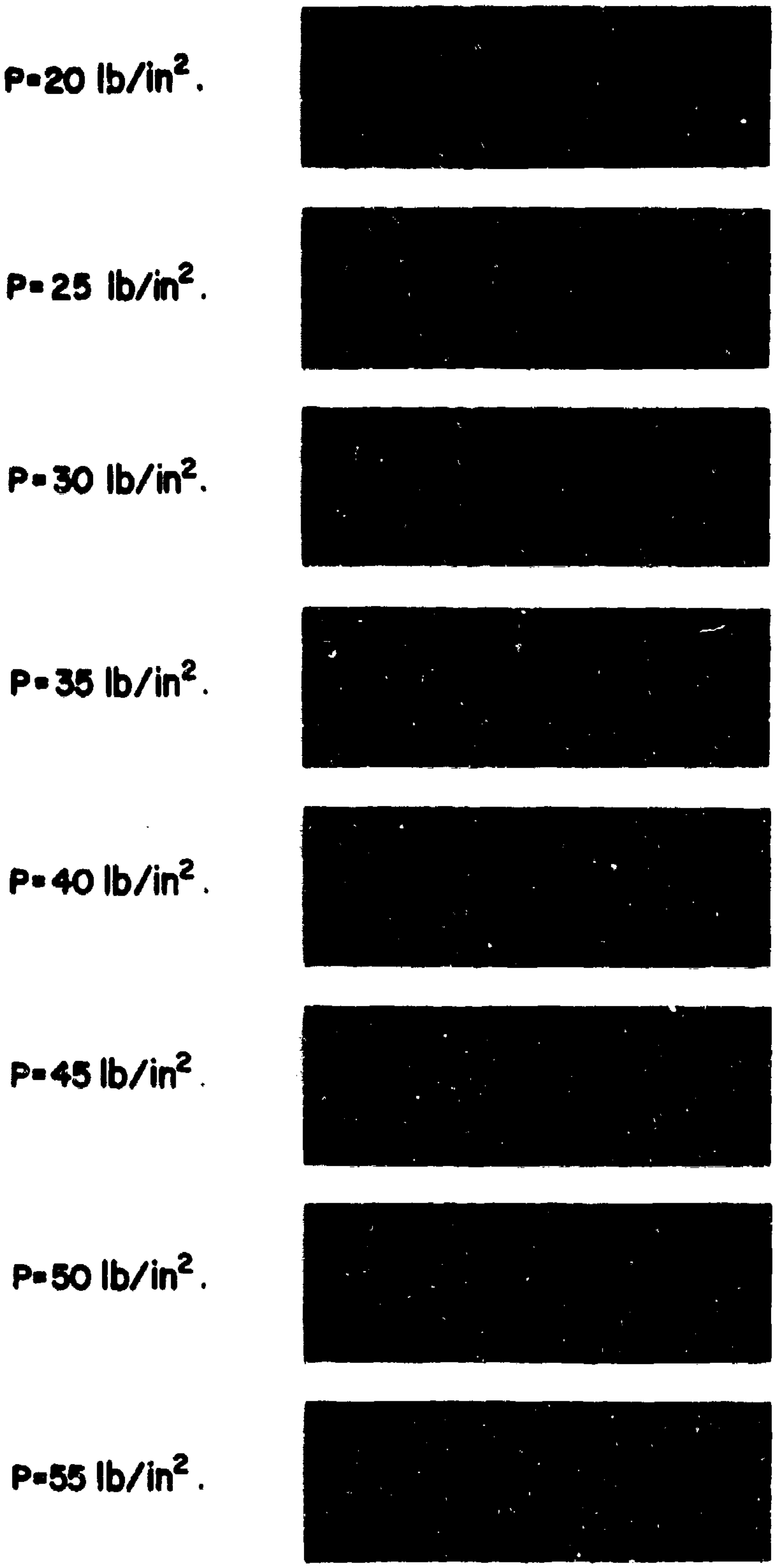
The two convergent jet nozzles described in this report had essentially the same type of internal profile, giving a gradual transition, formed by tangential circular arcs, from the parallel-section air-supply manifold to a narrower parallel-section orifice. Thus the jets issuing from them may be considered as 'choked jets' (by definition, jets whose exit pressures exceed the local ambient pressure and whose average exist velocity is that of sound, since the nozzle has minimum cross-sectional area at the orifice.) A spatially periodic jet efflux is formed under these conditions, as the pressure differential across the nozzle gives rise to a Prandtl-Meyer expansion radiating from the periphery of the orifice, which reduces the static pressure at the jet boundary to the ambient pressure, the first Mach lines of the expansion cutting almost perpendicularly across the jet (Fig. 15). As a result, the flow expands outwards and the jet boundary takes on a convex curvature. An 'expansion cone' is formed in front of the exit, along the axis of which the flow velocity will have a steadily increasing Mach number with distance from the nozzle. The Mach lines extend to the opposite boundary of the jet and are reflected as compression waves, reconverging to form the termination of the first 'cell' and restoring the static pressure to virtually its original value. Consequently the process is then almost repeated along the axis until turbulent mixing with the external atmosphere at the jet boundary inhibits the formation of further periodic structure.

A distinctive feature of periodic jets is the formation of shock-waves in the efflux. In Fig. 16 a series of shadowgraphs shows the effect of pressure increases on a jet issuing from a 1/2-inch diameter convergent nozzle. The conical shock with slightly concave sides which appears at the end of each cell



FORMATION OF SHOCK WAVE IN PERIODIC JET EFFLUX

FIGURE 15



SPARK-SHADOWGRAPHS OF PERIODIC JET EFFLUXES

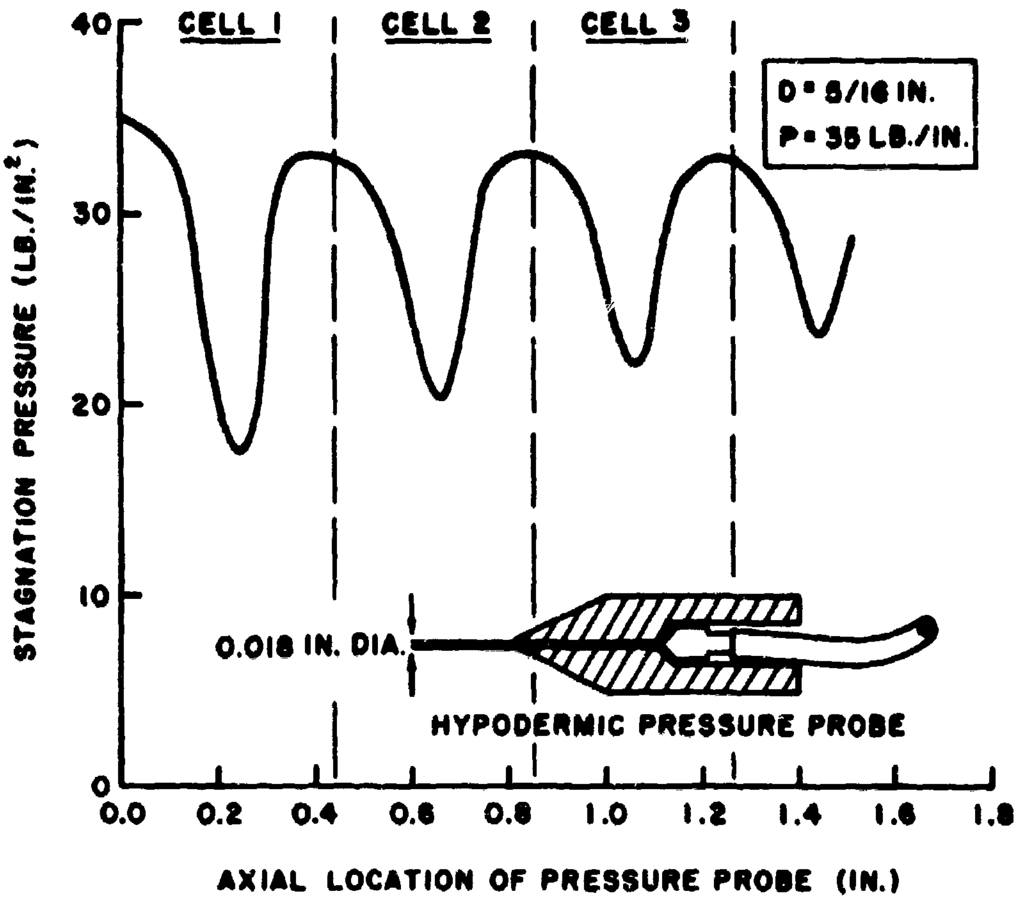
FIGURE 16

is generated by the compressive Mach waves that are reflected from the jet boundary in the vicinity of the nozzle, as shown in Fig. 15. (Fig. 15 is based on the shadowgraph in Fig. 16 displaying the periodic jet of 40 lb/in^2 excess pressure.) These Mach waves coalesce at the downstream part of each cell to form the shock discontinuity. As the pressure is increased the cells lengthen and the conical shock grows in strength until, at an excess pressure of approximately 43 lb/in^2, a normal truncation appears on the tip of the compression cone. This normal shock grows in area with further pressure increases and results in a breakdown of the regular periodicity of the jet, since the velocity change across the perpendicular disc-shaped discontinuity gives rise to a core of subsonic flow at jet axis, which gradually mixes with the surrounding supersonic flow. This is clearly displayed by surveys of the stagnation pressure along such jets.

Stagnation Pressure Distributions Along Periodic Jets

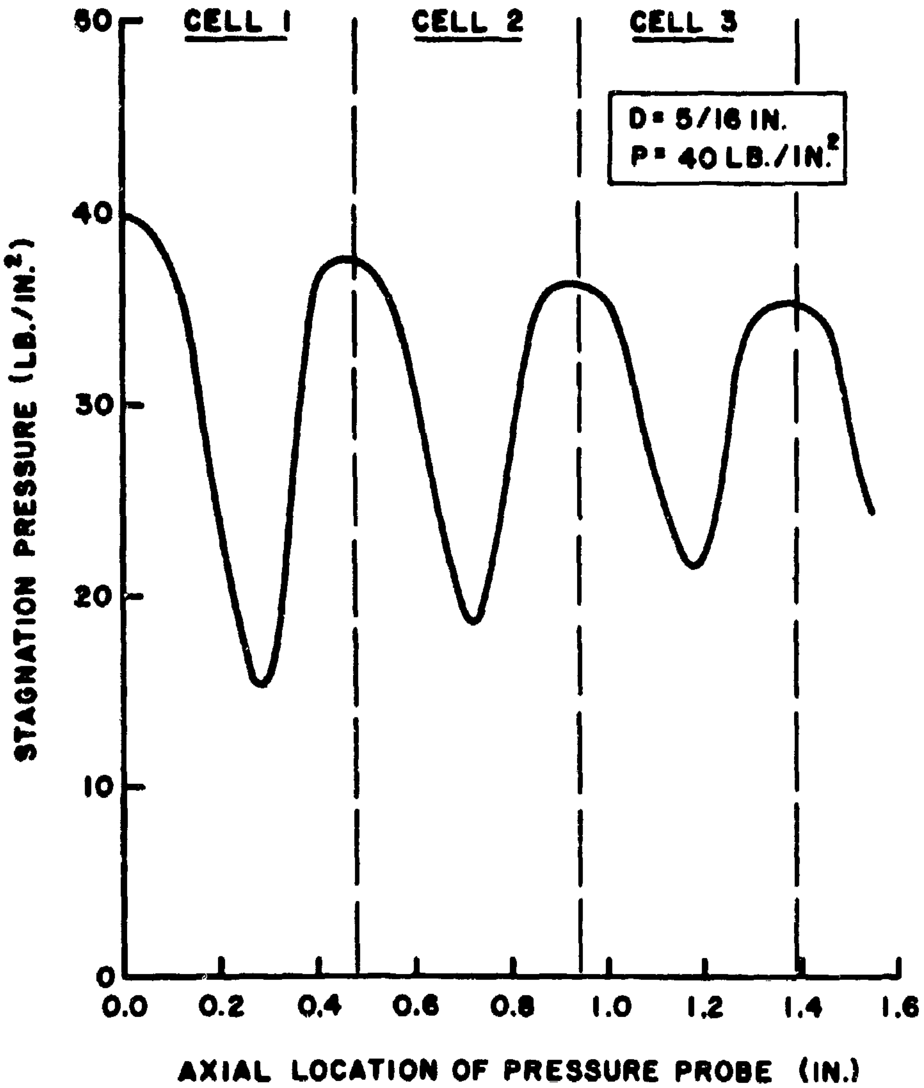
From the foregoing considerations of the flow variations occurring along a choked jet, it will be apparent that there must simultaneously be corresponding fluctuations of the static pressure along such a jet. To gain further information on this aspect, a series of tests were made using Pitot-tube probes of two different configurations. For the initial series, a very fine hypodermic probe (Fig. 17a) was connected to a Bourdon gauge and the probe point moved along the axes of symmetry of the periodic jets. Since the external diameter of the probe was very small, the separation region in front of it was of comparably small scale and the stagnation point was considered to be situated at the probe tip. Hence, the pressures indicated by the assembly related to conditions in a very small region on the axis behind the detached shock at the probe tip.

Figs. 17d show the periodically varying pressure along the axes of jets having various nozzle excess pressures, and the relationship of these pressure changes to the cell structure. The amplitude of the variation can be seen to increase as the excess pressure was raised, until a point was reached (at approximately 43 lb/in^2) where the normal truncation appeared in the compression cones; thereafter the pressures measured on the jet axis remained at a value of 8 lb/in^2 or less, for some distance along the efflux, and gradually increased as the subsonic jet core mixed with the surrounding high-velocity fluid.



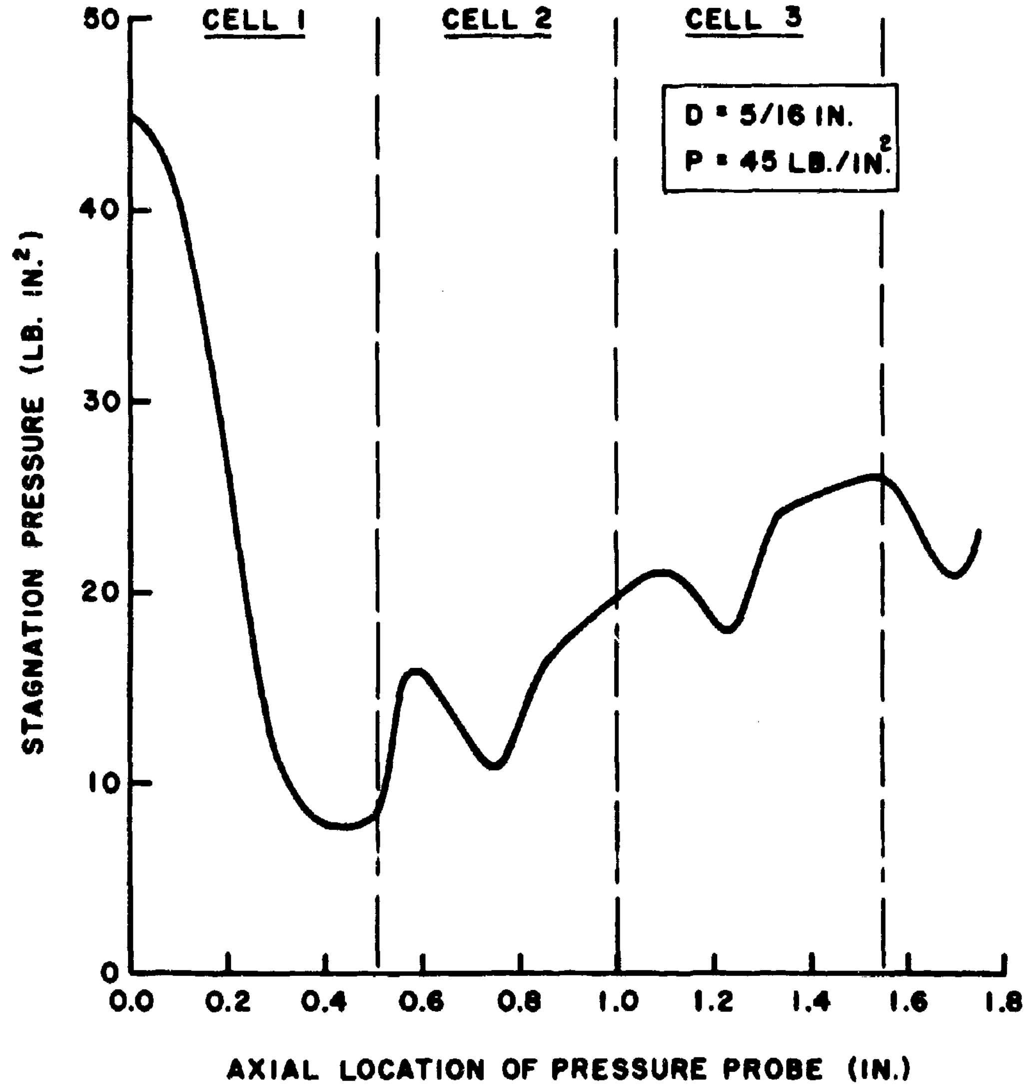
STAGNATION PRESSURE DISTRIBUTION ALONG CHOKED JET
AS MEASURED BY FINE PROBE

FIGURE 17a



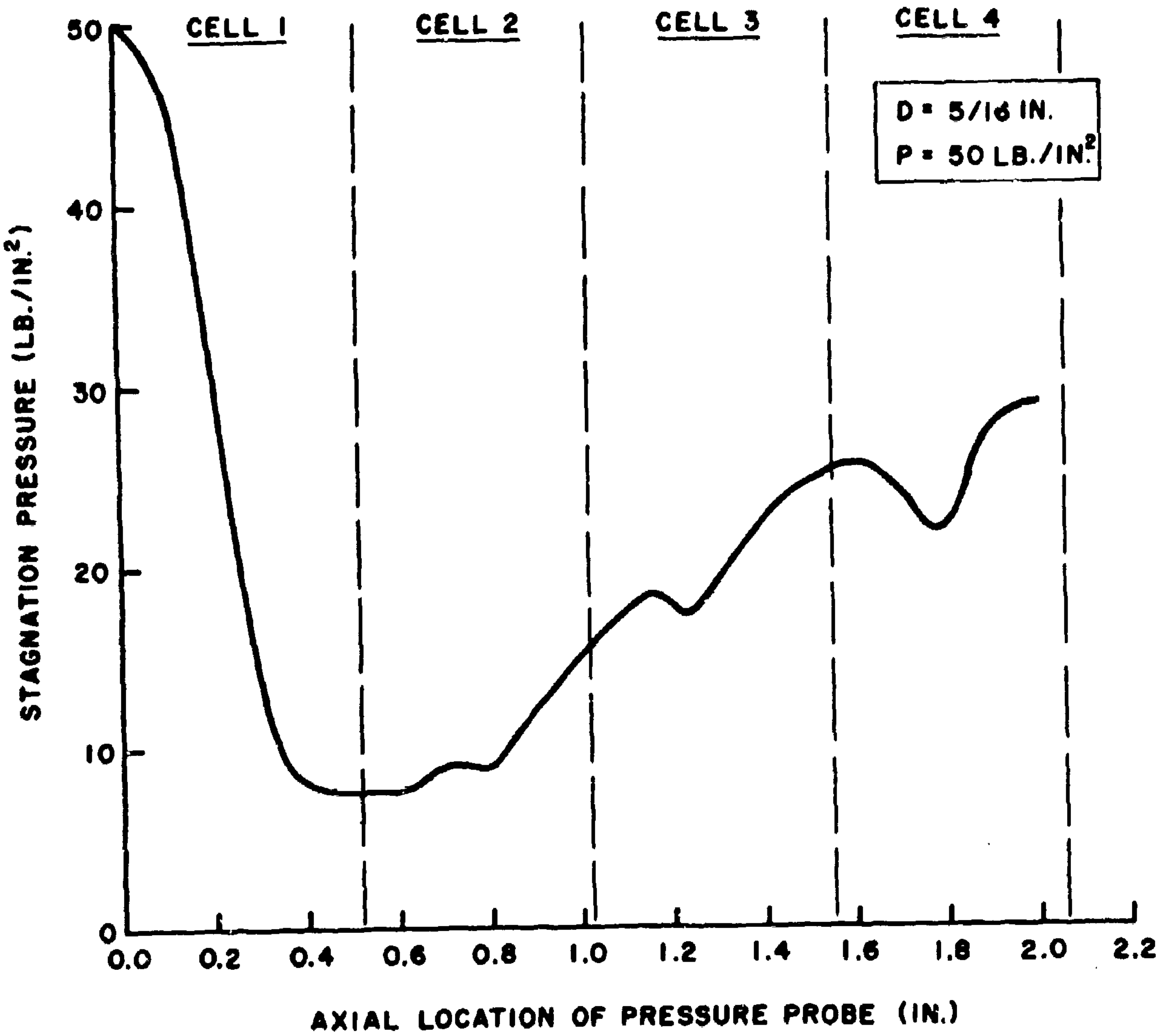
STAGNATION PRESSURE DISTRIBUTION ALONG CHOKED JET
AS MEASURED BY FINE PROBE

FIGURE 17b



STAGNATION PRESSURE DISTRIBUTION ALONG CHOKED JET
AS MEASURED BY FINE PROBE

FIGURE 17c



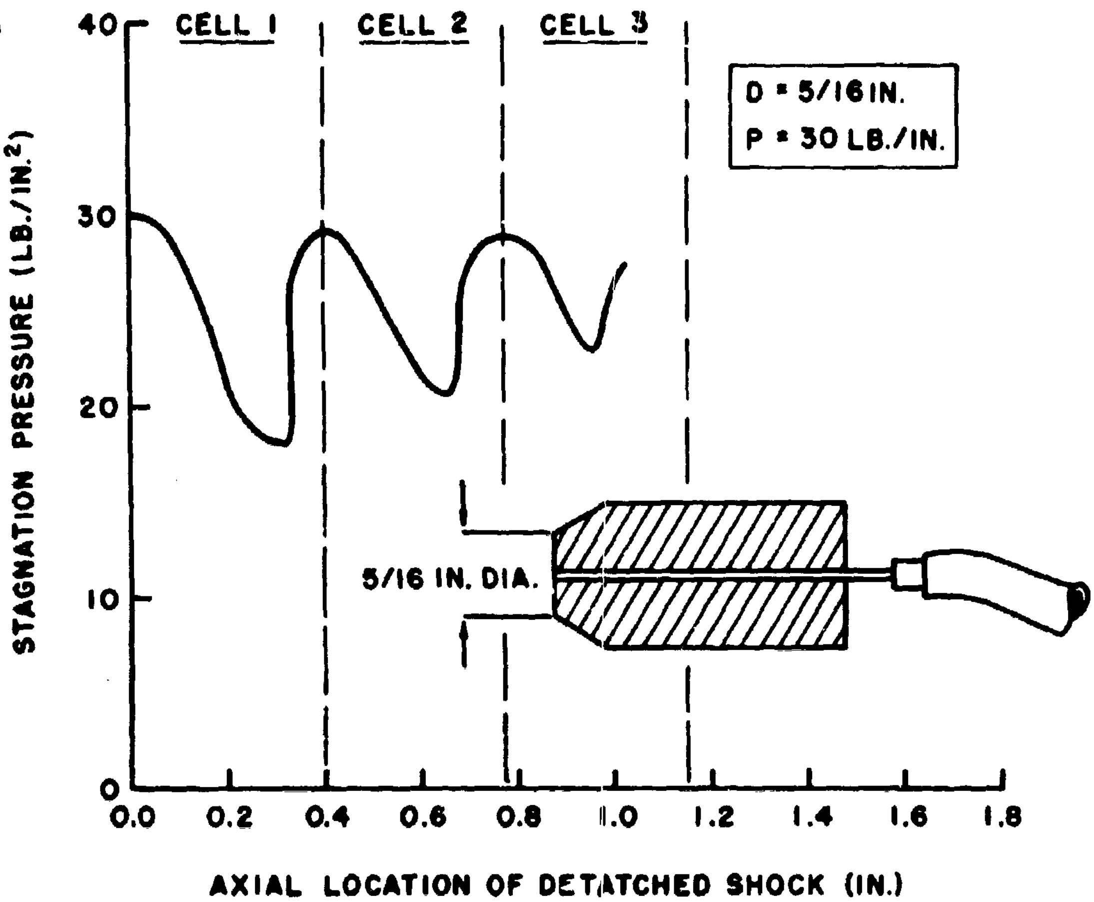
STAGNATION PRESSURE DISTRIBUTION ALONG CHOKED JET
AS MEASURED BY FINE PROBE

FIGURE 17d

Figs. 17 and 18 invite comparison with Figs. 14a to 14f where the regular pressure periodicity coincides with the repeated frequency responses and the aperiodic pressure distributions are linked with continuous oscillation of the cavity at all nozzle-to-cavity spacings. It may be intimated here that the aperiodic jet flow is more unstable due to the high radial velocity gradients, and this will bear directly upon any criterion for oscillation. (Note the similarity to the effect of a destabilizing trip, a leading feature of which is its low velocity wake.)

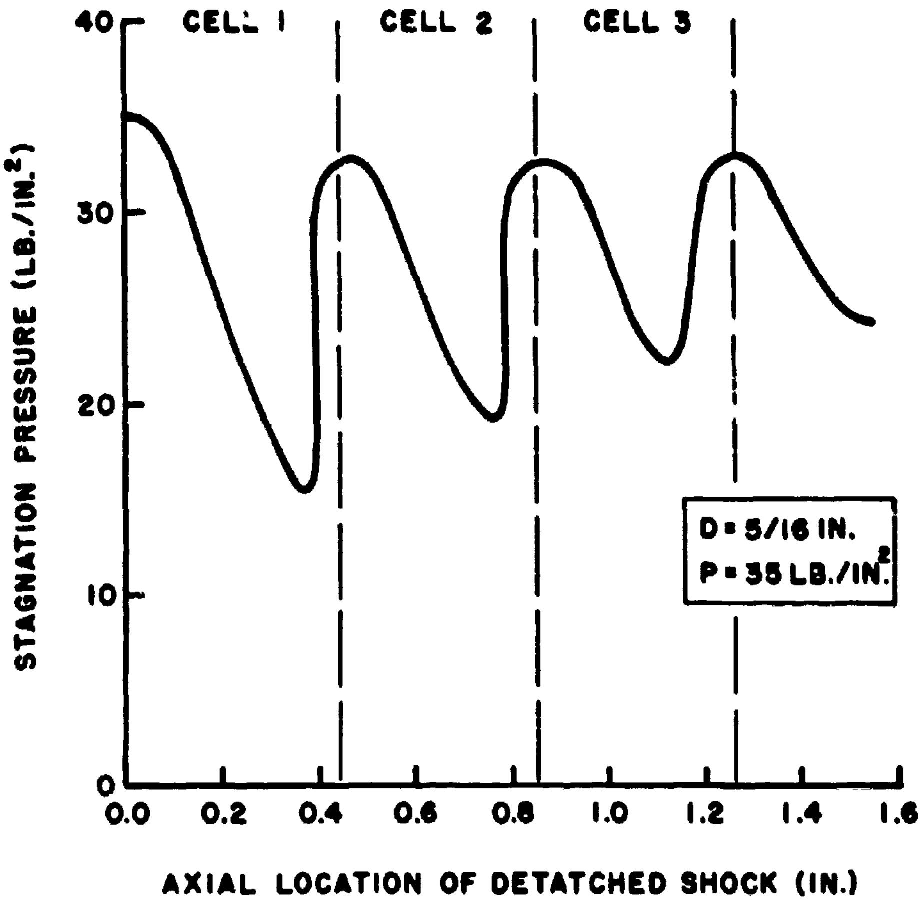
The second pressure survey was undertaken to measure the stagnation pressures behind the detached shock present during cavity resonance. In this case the probe was of the form shown in Fig. 18, consisting of a blunt body of the same profile as the cavities and having a narrow bore along its axis which was connected to a Bourdon pressure gauge as before. When placed in a jet efflux, the detached shock took up a position in front of the probe depending on the stand-off distance. These results are plotted in Fig. 18 for varying positions of the shock. They differ somewhat from the fine-probe surveys insomuch as the characteristics have a much steeper slope in the pressure recovery zones and more pronounced peaks at the maxima and minima.

During these pressure surveys it was found that the shock became unstable when located in the pressure recovery zones of the jet effluxes. This condition has occurred mainly for pressures in excess of 35 lb/in^2 and persisted for only a short distance along the axis. For larger baffles the instability was detected at lower pressures and over much wider limits. It may be surmised that the oscillations arose as a result of some form of resonance in the stand-off zones, since the wavelengths of the emitted sound appeared to be proportional to the distance of the shock from the probe-face--as postulated by Mørch in a theory for the instability of detached shocks[52].



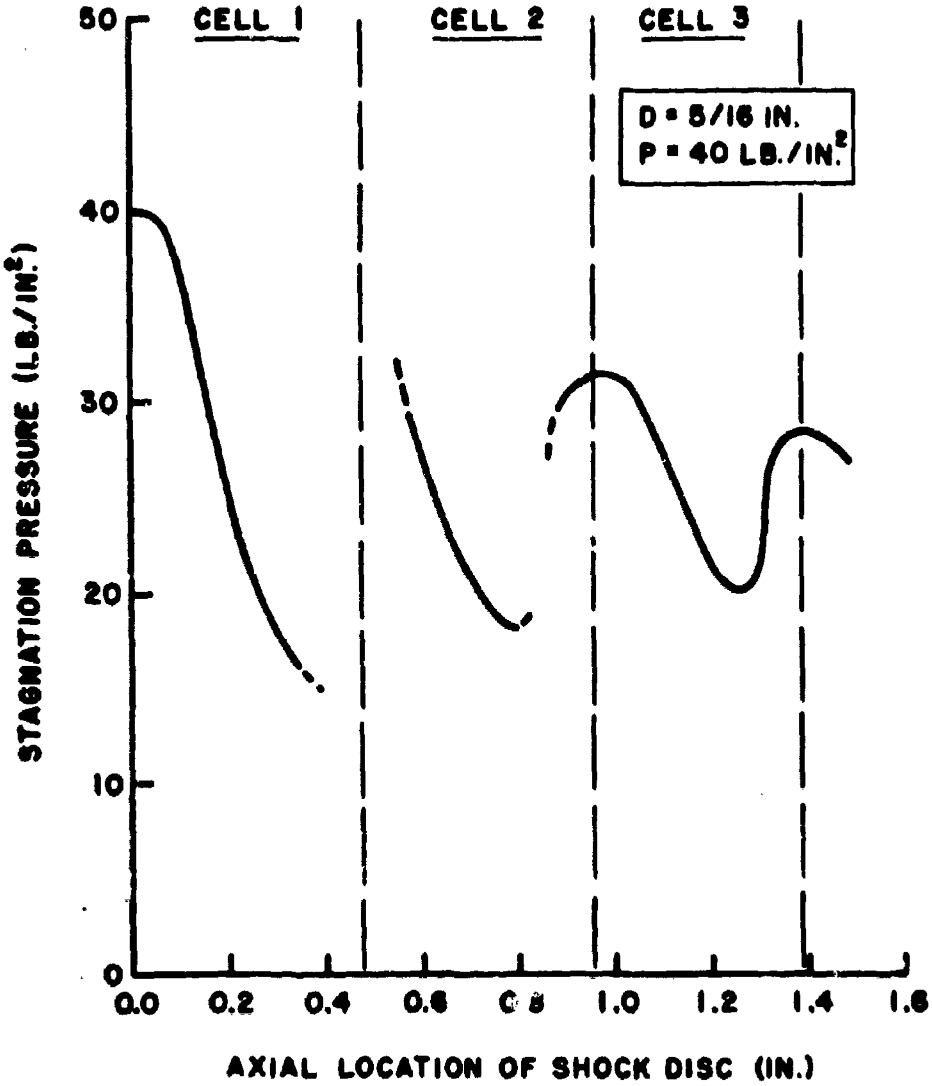
STAGNATION PRESSURE DISTRIBUTION ALONG CHOKED JET
AS MEASURED BY BLUNT PROBE

FIGURE 18a



STAGNATION PRESSURE DISTRIBUTION ALONG CHOKED JET
AS MEASURED BY BLUNT PROBE

FIGURE 18b



STAGNATION PRESSURE DISTRIBUTION ALONG CHOKED JET
AS MEASURED BY BLUNT PROBE

FIGURE 18c

However, when the excess pressures exceeded 43 lb/in^2, severe instability of the shock disc was encountered at all points along the jet axis for all baffle diameters, and consequently, pressure measurements behind the shock were impossible. The instability took the form of very high-frequency oscillations, the radiated acoustic energy increasing as the size of the baffle increased. Tests on a jet impinging on a 12-inch diameter baffle indicated the presence of acoustic feedback phenomena, since an auxiliary baffle with its plane horizontal to the jet axis and held within a few diameters of the jet efflux was found to have a major influence on the acoustic output. As the auxiliary reflector was moved perpendicularly to the jet flow, the acoustic output increased to a maximum and then fell off--in some cases the sound emission ceased completely--as the surface traversed a distance equal to one wavelength of the emitted sound. From these observations it is inferred that the unstable nature of the aperiodic jet, together with sound reflected from the interaction zone back to the nozzle, gave rise to flow perturbations that served to drive the oscillations.

The data made available by the foregoing surveys showed that contributary factors to the modus operandi of a Hartmann whistle might possibly depend on (among other effects): feedback of disturbances from the cavity to the nozzle giving rise to jet perturbations, analogous to that giving rise to 'choked jet noise'[62], effects arising from the oscillating shock wave along rectilinear cavities, and detached shock instability. In consequence it was necessary, in order to obtain a complete description of the mechanism, to conduct tests on an oscillating system in which as many of the above-mentioned effects as possible could be ruled out as non-contributary.

Excitation of a Helmholtz Resonator by Periodic Jets

Several of the foregoing factors could be discounted when the oscillations of a very low-frequency whistle were considered. This condition was ideally satisfied by adding a large-volume Helmholtz resonator to the ends of the previously described cylindrical cavities, as shown in Fig. 19. The device, which was first used by Hartmann in his earliest studies of the phenomenon and referred to by him as the 'pulsator' appears to have been overlooked in all subsequent researches. By choice of suitable dimensions

THE HARTMANN-HELMHOLTZ RESONATOR

FIGURE 19

for the resonant cavity it was possible to obtain an oscillatory system having an extremely low frequency, with which all the flow variations occurring during the course of a resonance cycle could be visually examined. For the purposes of the study described here, a flanged cylindrical cavity of 6 in. diameter and 500 cu. in. volume was provided with a set of replaceable end plates into which either 1/2 in. or 5/16 in. diameter orifices could be fitted, together with various forms of pressure-recording attachments, as required. The tubes forming the resonator exits were usually 2 ins. long, or less.

For the conditions of small-perturbation theory, the Helmholtz resonator may be considered to oscillate by virtue of a mass of gas contained in the 'neck' moving with small amplitude against the resistance provided by compression of the remaining gas within the cavity; the frequency of the resonator described above, when fitted with a 5/16 in. orifice would have been in the region of 40 c/s. However, when excited by a periodic jet, the cavity was found to oscillate at a frequency varying between 10 c/s and 0.5 c/s depending on the jet excess pressure and the spacing of the cavity and the nozzle. Since the wavelength at these frequencies was very much greater than the cavity's longest dimension, it was evident that there could be no travelling shock-wave within the resonator (such as occurred in the rectilinear cavities) that could contribute to a mechanism for triggering each successive cycle, as postulated by Hartmann.

Thus, the driving mechanism for the oscillations of resonant cavities placed in spatially periodic jet effluxes cannot be critically dependent on feedback, or any 'tripping' of the cycle, by simple wave or shock motion within the cavity. It must account for the stable and unstable zones encountered in the jet efflux, and also the lack of stable zones when the geometric periodicity of the jet breaks down. The postulated mechanism should permit the oscillations to be quite impulsive in their commencement and cessation--there being generally no steady increase in oscillatory amplitude from a small disturbance, as is the case with most other forms of discrete-frequency sound generation by fluid flows.

The Mechanism of the Hartmann Whistle

With the help of studies of the Hartmann-Helmholtz whistle, a mechanism is suggested for the initiation and maintenance of the oscillations. Due to the expanded time-scale of the oscillations of this resonator it was possible to examine, visually, a complete cycle without resorting to stroboscopic illumination or phased shadowgraphs. The cycle appeared to be essentially the same as that of any small cavity , except that the flow in and out of the Helmholtz resonator was more clearly defined, the debouchement taking the form of a jet flow of variable excess pressure and the zone of jet interaction being further removed from the vicinity of the cavity orifice.

The main features of its external flow variations appeared to be as follows:

(1) Consider the cavity mouth to be located in the jet flow at a point just downstream of a cell division, i.e., at the downstream limit of one of the unstable zones.

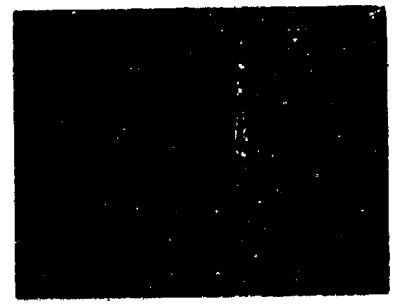
FIGURE 20

(2) The jet initially flows into the cavity with the detached shock located very close to the orifice--a position hereafter referred to as the 'downstream quasi-stable location' of the shock, as in Fig. 20a.

(3) As the cavity fills and the pressure within it increases, the separation region of stagnation flow downstream of the shock grows in volume, i.e., the shock stand-off distance increases.

(4) When the increasing stand-off distance causes the shock to move to where its stagnation pressure decreases (across the cell division) it is impulsively transferred through a definite distance upstream, initiating a radiated pressure wave as the cavity procedes to debouch in the form of a second spatially periodic jet. The shock is now located at the 'upstream quasi-stable location', as in Fig. 20b.

(a) CAVITY PRESSURE = 33.5 lb/in^2.
(DOWNSTREAM QUASI-STABLE SHOCK LOCATION)



(b) CAVITY PRESSURE = 33.5 lb/in^2.
(UPSTREAM QUASI-STABLE SHOCK LOCATION)

(c) CAVITY PRESSURE = 27.5 lb/in^2.

(d) CAVITY PRESSURE = 23.5 lb/in^2.

SPARK-SHADOWGRAPHS OF AXIALLY INTERACTING JETS,
REPRESENTING THE OSCILLATIONS OF A
HARTMANN-HELMHOLTZ RESONATOR

FIGURE 20

(5) As the pressure in the cavity drops, the normal shock gradually moves back downstream (Fig. 20c) until it reaches the limit of the range of its upstream quasi-stable location, (Fig. 20d), when it impulsively moves back to the cavity mouth which then commences to refill for the next cycle.

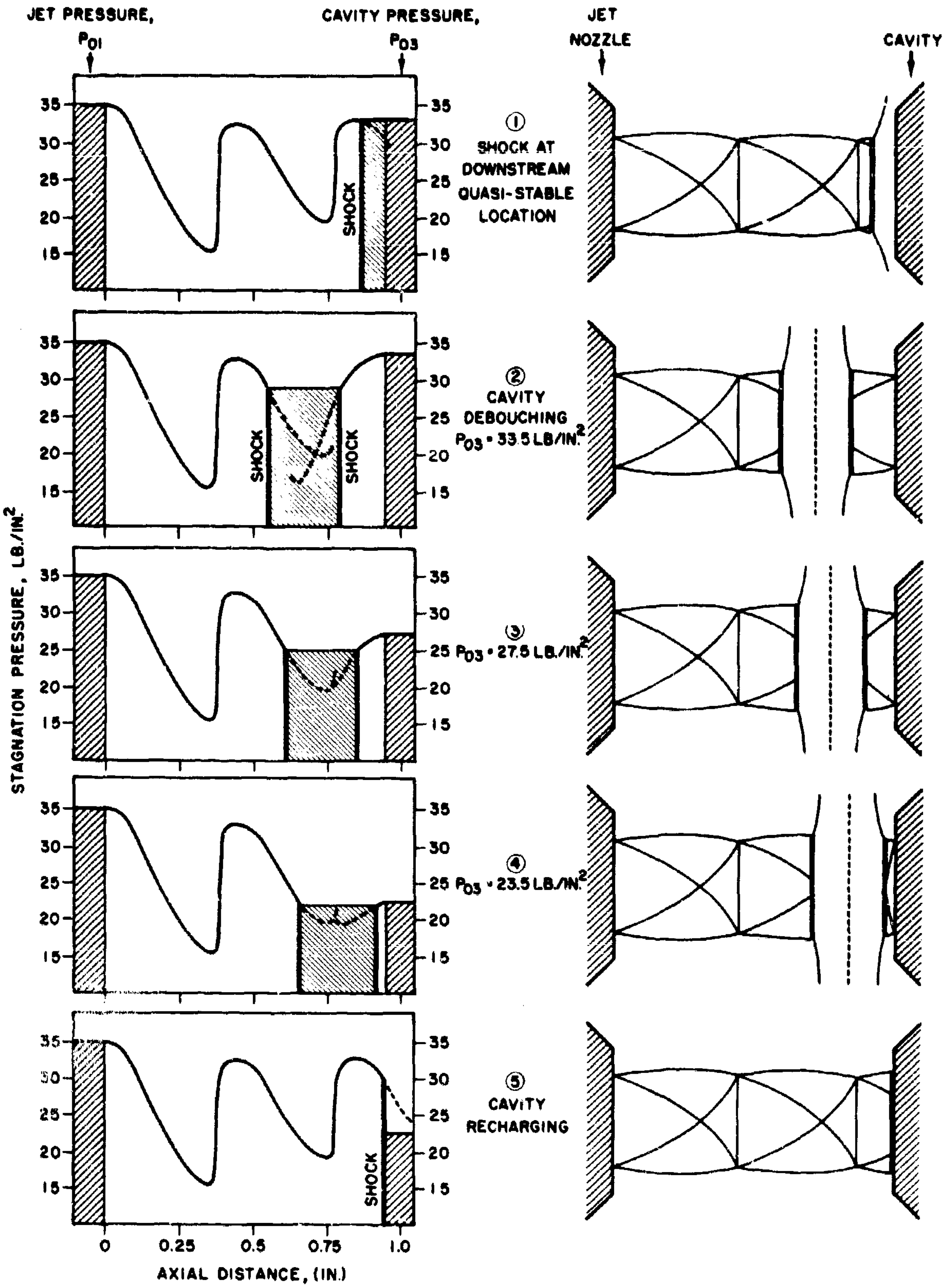
(6) With the cavity further downstream the shock remains at its downstream quasi-stable location, no oscillations being driven when the shock does not cross the cell division.

(7) Translation of the cavity in an upstream direction results in cavity oscillations of steadily increasing frequency until the upstream limit of the unstable zone is reached.

(8) Pressure measurements showed that no over-pressures were recorded at the closed end of the cavity, as occurred for the case of a 2-inch cavity, (Fig. 10), the pressure variations remaining within the limits of the stagnation pressure distribution encountered along the jet flow.

Since the interaction flows were shown to be of the form of two periodic jets, that phenomenon was studied a little further by arranging for the axial impingement of two identical jet effluxes. An auxiliary air-supply manifold, carrying a 5/16 in. diameter nozzle of the same internal profile as the fixed nozzle, was mounted on a moveable cross-slide and connected via a flexible pressure-hose to a separate control valve. A tapping was provided on the auxiliary manifold for measurements of the jet excess pressure. By selecting a given nozzle-to-nozzle spacing and fixed jet pressures, any part of the resonant cycle of a Hartmann-Helmholtz whistle could be 'frozen' and observed in detail. The shadowgraphs of Fig. 20 were obtained in this way, and measurements of the shock separations and stagnation flow widths were obtained from which the following modus operandi was developed.

The postulated driving mechanism for any cavity excited by a periodic jet is illustrated in Fig. 21 with reference to the case of a Helmholtz resonator. On the left, the over-all stagnation pressure distributions of the main jet and the variable-pressure jet emerging from the cavity are displayed, and in the right-hand column the corresponding interacting jet flows are illustrated.



STAGNATION PRESSURE DISTRIBUTIONS OF INTERACTING, PERIODIC JETS

FIGURE 21

(1) The cavity receives fluid from the jet flow until the pressure inside the cavity is equal to that existing behind the detached shock in its downstream quasi-stable position--a value that will vary with the location of the cavity (and thus of its normal shock) along the jet axis.

(2) If the cavity orifice is just downstream of a cell division, then the shock will be in a region where the stagnation pressure distribution curve maximizes.

(3) If the detached shock crosses the cell division (the selected location is in the region of the downstream termination of one of the unstable zones), due to either an increase in jet pressure and the consequent lengthening of the cell dimensions, or movement of the cavity in an upstream direction, then the shock disc will be transferred to a region where stagnation pressure drops rapidly with axial distance. (This corresponds to movement of the shock from a position of neutral equilibrium to one of unstable equilibrium. Movement in the opposite direction merely transfers the separation zone to a point of stable equilibrium where pressure increases with distance from the cavity--the so-called 'stable zone').

(4) Since, in this condition, the cavity pressure exceeds the stagnation pressure corresponding to the shock's location, the pressure imbalance results in the shock moving upstream to the next point of quasi-stable equilibrium.

(5) The cavity proceeds to debouch, the high excess pressure within it causing the emergent fluid to form a periodic jet efflux. Between the two impinging jets there will be an interface with equal pressures on either side. Consequently the stagnation flow of each jet can be approximated by a wall flow of the jet impinging on an infinite baffle--the separation of the shock from the interface being determined by the jet excess pressure. The upstream and downstream shocks take up positions in the two jet effluxes at points producing equal stagnation pressure.

(6) As debouchment continues, the cavity pressure falls and the interacting flow zone moves toward the cavity mouth until the equal stagnation pressures at the common "plane" can no longer be maintained. This flow pattern then collapses and the periodic jet flow again enters the cavity, the beginning of the next cycle.

(7) This proposed mechanism appears to be valid for any location of the detached shock as long as it is in a region of the jet efflux where the stagnation pressure behind it falls with distance from the cavity orifice. At points where the pressure differential between the stagnation pressures of the two quasi-stable points is reduced, the re-cycling time for the cavity will be of shorter duration, and in consequence the frequency of oscillation of a Helmholtz resonator will increase as the cavity is moved upstream through an unstable zone.

(8) The re-cycling time of this series of events for any cavity is evidently dependent on the rate at which the cavity charges and debouches, and hence the frequency of oscillation will also be governed by (although different from) the resonant frequency of the cavity. Reviewing Fig. 7 in the light of the proposed driving mechanism it can be seen that the time taken for the 2-inch cavity to debouch (the half-periodic time) was less than the time taken for the normal shock to make a complete transit to its maximum outer quasi-stable position, although the mechanism for the driving of the oscillations seems identical to the above.

(9) All cavities will thus tend to oscillate at their fundamental frequency when the normal shock has sufficient 'axial freedom' in which to make large-amplitude oscillations. As the cavity is moved upstream through the stable zone the distance over which the shock can oscillate is reduced and the mode of oscillation jumps to a some higher harmonic frequency, where the system oscillates with reduced linear movement of the shock.

CONCLUDING REMARKS

This tentatively proposed mechanism for the initiation and maintenance of the oscillations of a Hartmann whistle when excited by a strictly periodic supersonic jet amplifies that which was originally postulated by Hartmann in 1924. Some shortcomings of the original theory have been clarified, largely by the identification of the bi-stable condition of the stagnation point. Attention is now being turned to set up a suitably rigorous theoretical description of the mechanism, the important role of the jet structure and the associated variable stagnation pressure (and therefore variable entropy) in the jet having been established. This throws some light upon such questions as the failure of the two-dimensional system to oscillate (different pressure distribution) while the hydraulic analog, recently brought into use, does so. Work is still in progress in respect of the differing aspects of what seems to be a somewhat similar mechanism for the instability for very high-pressure aperiodic jet flow, and for the de-stabilizing trips causing oscillations of an otherwise stable whistle configuration--particularly in relation to the case of the 'stem-jet'.

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The Hartmann whistle, in its most basic configuration, consists of a flat-bottomed, cylindrical cavity which is axially aligned with a supersonic air jet of the same diameter. Discrete-frequency oscillations of the enclosed air column are driven at large amplitudes when the cavity is located within certain regions of the cellular structure of the jet. An optical and acoustical study of the phenomenon is described, together with that of the Hartmann 'pulsator'. In the latter form the whistle has the small cavity replaced by a large Helmholtz-type resonator with the same orifice diameter, resulting in a large-amplitude aeroacoustic oscillator with a periodic time of several orders of magnitude greater than for the regular whistle. The underlying cause of the newly discovered bistable condition of the normal 'shock-disc' located in the airstream between the nozzle and the cavity orifice is an important aspect which makes possible a (presently qualitative) theory of operation which accounts for the principal features of the Hartmann whistle and its direct derivatives. Some other aspects still requiring further elucidation and which are the subject of continuing effort are mentioned. The Report includes a brief review of the currently available literature pertaining to the phenomenon.

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